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SURFACE OIL DISPLACEMENT BY U.S. COAST GUARD 82-FOOT CUTTERS.(U)
JAN 79 S P KRAUS , R W TENNANT , C HANSEN N62583-78-M-R-132

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LEVEL IV (12)

SURFACE OIL DISPLACEMENTS BY
U. S. COAST GUARD 82-FOOT CUTTERS

Steven P. Krause
Ralph W. Tennant
Carrie Hansen

FEBRUARY, 1979

FINAL REPORT

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U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT

NAVAL SEA SYSTEMS COMMAND
SUPERVISOR OF SALVAGE
WASHINGTON, D.C. 20362

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16. Abstract

The U. S. Navy, in cooperation with the U. S. Coast Guard, is conducting design and feasibility studies for a portable oil sorbent spreader and retriever for use aboard military and commercial vessels-of-opportunity during oil spill clean up operations. As part of this program, the U. S. Navy's Civil Engineering Laboratory (CEL), Port Hueneme, California contracted with the Geography Remote Sensing Unit (GRSU), University of California, Santa Barbara to provide field support and data analysis services in conjunction with sea tests to determine the effects of vessels on surface oil slicks. A total of four sea truth data acquisition cruises were conducted through natural oil seeps in the Santa Barbara Channel, California between December 1977 and February 1978. Coast Guard 82-foot patrol boats served as representative vessels of opportunity for the tests. This report describes the data collection program associated with the sea tests and the results of our analysis of field data.

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METRIC CONVERSION FACTORS

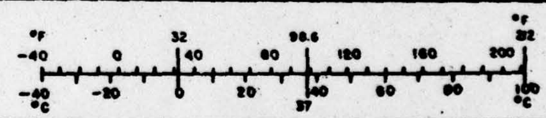
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The U.S. Navy, in cooperation with the U.S. Coast Guard, is conducting design and feasibility studies for a portable oil sorbent spreader and retriever called MSORS (Mechanized Sorbent Oil Recovery System) for use aboard military and commercial vessels-of-opportunity during oil spill cleanup operations. As part of this program, the U.S. Navy's Civil Engineering Laboratory (CEL), Port Hueneme, California contracted with the Geography Remote Sensing Unit (GRSU), University of California, Santa Barbara to provide field support and data analysis services in conjunction with sea tests to determine the effects of vessels on surface oil slicks. Specific objectives of the sea test program were to:

- document changes in surface oil expression and thickness as vessels-of-opportunity transited oil slicks. These tests were to be performed under a variety of sea state conditions, vessel operating speeds, and vessel headings.

- Using these data determine optimum locations for the placement of spreading and retrieval equipment on vessels-of-opportunity to maximize oil cleanup probability.

The test program was two part, consisting of a sea truth/data gathering phase and a laboratory analysis phase. A total of four sea truth data acquisition cruises were conducted through natural oil seeps in the Santa Barbara Channel, California between December 1977 and February 1978. Coast Guard 82-foot patrol boats served as representative vessels of opportunity for the tests. During each test day, GRSU investigators provided surface and aerial still and motion photography to document all conditions in the test area and record the effects of moving vessels on oil. Surface and subsurface oil sampling was also conducted prior to, during and following vessel runs through oil seeps to provide a quantitative data source for determining oil slick thickness changes. Reduction and analysis of sea truth data were accomplished at the Geography Remote Sensing Unit and UCSB Department of Chemistry laboratories.

This report describes the data collection program associated with the sea tests and the results of our analysis of field data. The report is divided into seven major sections. Part A locates the Santa Barbara Channel test site and provides the rationale for its selection. Part B documents the data collection procedures used for establishing the effects of moving vessels on surface oil slicks. Part C explains the procedures employed to process and format the correlative sea truth data. Part D provides descriptive information for each test day including the number of individual transects completed, vessel speeds and headings, surface oil slick concentrations, and oceanographic and climatological conditions.

Part E contains a detailed analysis of vessel/oil slick interactions for selected transects. Part F presents summary findings and conclusions concerning oil fate and behavior as related to vessel operations. Part G includes recommendations for the location of dispersion/retrieval equipment on vessels-of-opportunity to maximize oil recovery performance.

A. PROGRAM TEST SITE

All sea trials associated with the test program were conducted in the Santa Barbara Channel, California. The test site, located approximately 12 miles west of the City of Santa Barbara and adjacent to the UCSB campus, was selected due to the chronic natural oil and gas seepage from subsurface formations. The natural seeps provided reliable surface oil accumulations under a range of meteorological and oceanographic conditions. While the volumes of oil released by the seeps and resulting surface concentrations could not be controlled, this tradeoff was considered to be minor when compared to the difficulties and time delays inherent in acquiring necessary federal and state permits to release oil from vessels. The approximate boundaries of the test area are shown in Figure 1.

An estimated 50-200 barrels of crude oil are released daily from natural seeps within the confines of the test site (Allen and Schlueter, 1969; Wilkinson, 1972). The seeps located directly off Coal Oil Point are especially prolific; often covering the ocean surface with near contiguous oil slicks several square miles in area. Thickness characteristics exhibited by this natural seep oil and actual surface concentrations are primarily dependent on weather conditions and sea state. When the offshore area experiences high winds (>ten knots) and/or high seas/swells (>six feet), rapid evaporation of volatiles occurs and slicks spreading on the surface are characteristically thin (.0001 inches or less) and elongated (with narrow surface profiles downwind from the point of origin). With lesser wind and wave conditions, surface evaporation is retarded and oil slicks may be thicker and more expansive in aerial coverage. The thickest, most extensive oil concentrations generally occur following several calm days when oil is permitted to buildup on the surface without being transported out of the local area. Under these conditions, long windrows of thick, emulsified oil are typically found extending downwind from seep source areas. These oil windrows often form protective barriers downward from freshly surfaced soil and may surround large oil slicks in excess of five square miles (Estes and Kraus, 1976; Kraus and Estes, 1976).

Oil was present on all test days, although the concentrations varied considerably depending on wind conditions, wave/swell height, and ocean currents. (see Appendix C).

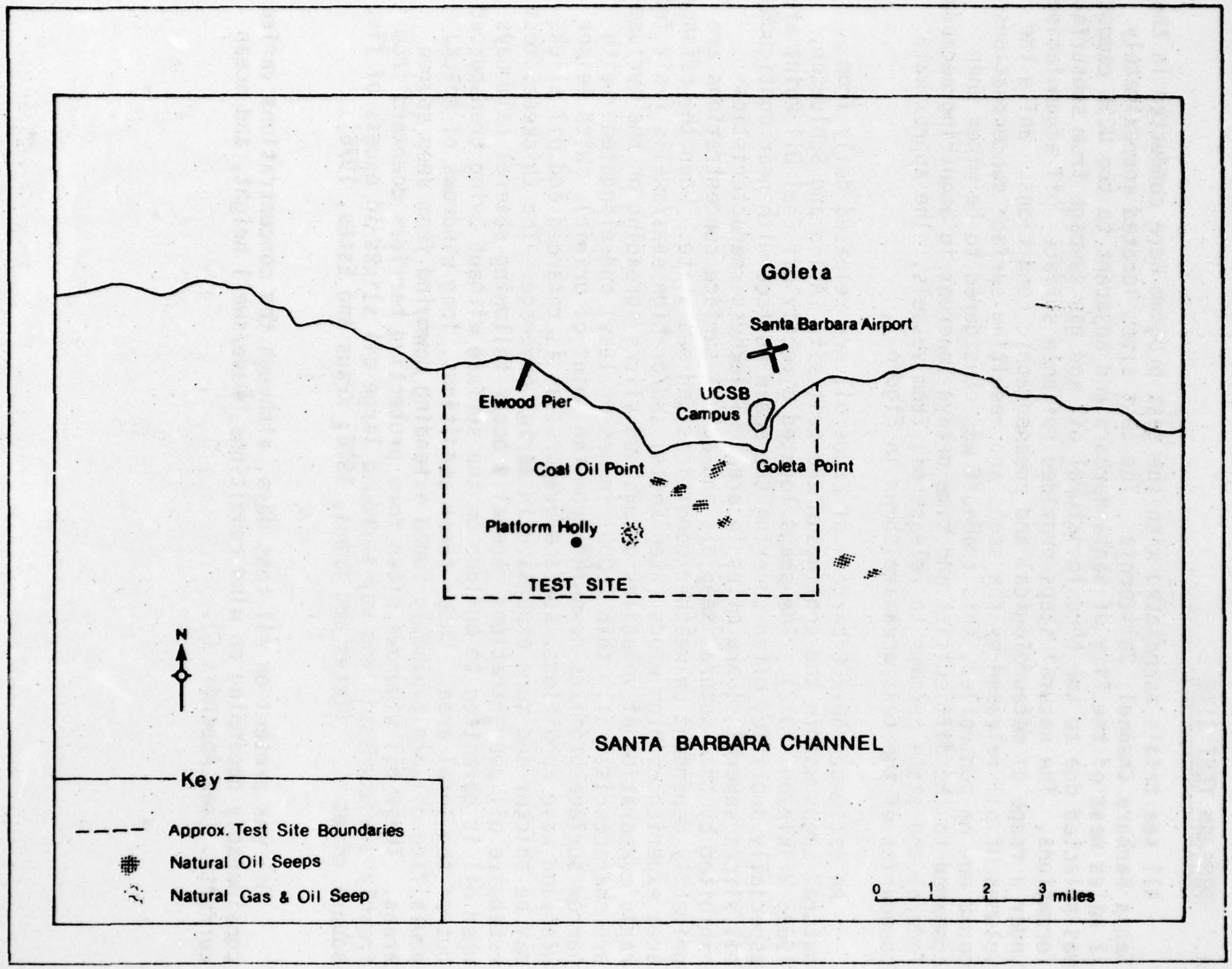

FIG. 1. Santa Barbara Channel Test Site

B. DATA COLLECTION

The sea truth data acquisition program described in this section was designed to provide GRSU investigators with quantitative and qualitative data to:

- Establish baseline surface and subsurface oil conditions in the Santa Barbara Channel test site prior to individual ship transects,
- Record baseline meteorologic and oceanographic conditions over the general test area for each test day,
- Document fate and behavior of surface/subsurface oil during and following vessel runs through natural seeps with particular emphasis on changes in the distribution and thickness characteristics of surface oil and the volume of oil entrained in the water column,
- Determine preferred (recommended) angles of attack, with reference to sea and swell, and optimum operating speeds to facilitate maximum oil recovery success by vessels-of-opportunity employing oil chip spreading/recovery systems,
- Make recommendations for placement (location) of proposed spreader/retrieval devices on vessels-of-opportunity.

A comprehensive data acquisition and verification program employing still and motion picture photography, surface and subsurface oil sampling, and onsite visual observations was developed to meet program objectives. Light aircraft, helicopters, 82-foot Coast Guard patrol cutters, and small surface craft were used as camera and/or sampling platforms to collect data on surface/subsurface oil conditions and the disturbance/displacement patterns created by vessels transiting through oil slicks. Meteorological and oceanographic data also were complied for each test day to provide baseline information for correlating potential vessel oil recovery efficiency as a function of sea state, wind, and currents. The following approaches were used by GRSU investigators to document oil slick location, aerial extent. and thickness characteristics; determine the effects of transiting vessels on surface oil slicks; and record weather and sea surface conditions.

1. Oil Slicks -- The location and areal extent of natural oil slicks surfacing in the test area was documented for each sea cruise day using aerial photography and visual observations. A chartered, single-engine Cessna 182 aircraft served as an airborne camera/observation platform during the December 2 and 8, 1977 cruises; a Coast Guard turbine powered Sikorsky HH-52A helicopter was used as a camera ship for the December 15, 1977 and February 21, 1978 operations. GRSU photographers employed hand-held 35mm and Super 8mm cameras to acquire aerial and near-surface color and color infrared still imagery and

near surface color movies of surface oil slick conditions in the test site for all four days. Aerial color movie footage was shot by GRSU photographers on December 2 and 8 using Super 8mm cameras and by a photographer from the Civil Engineering Lab on December 15 and February 21 using a 16mm camera. A list of film types acquired during each sea cruise day is contained in Table 1.

Estimates of oil slick thickness conditions prior to vessel runs and the fate and behavior of oil during and following ship transects were based on visual observations, aerial and near surface photography, surface sampling, and subsurface sampling. The sampling efforts, in particular, were designed to provide quantifiable data on oil fate and behavior as test vessels proceeded through slicks. Brief descriptions of the four methods employed to determine oil thickness/oil fate and behavior follow:

- Visual observation -- GRSU observers onboard the Coast Guard helicopters and light aircraft made preliminary oil film thickness estimates using a visual estimation method developed by Allen and Schlueter (1969) and since refined by other researchers. Basically, this method correlates oil thickness with oil film color. Data on oil film thickness patterns along test transects was annotated on rough field maps and recorded in flight logs.

- Aerial and nearsurface photography -- Color and color infrared slide and print film were imaged from aircraft and Coast Guard cutters during the tests to provide a permanent source for estimating oil slick thickness based on the correlation between oil film color and thickness characteristics. The nearsurface imagery acquired onboard the cutters was especially useful for analyzing changes in surface oil distribution and consistency as the test vessels proceeded through natural slicks.

- Surface sampling -- This method provided quantifiable oil thickness data for selected points along test transects, and served as a calibration source for the oil color-oil thickness correlation estimates obtained through photographic documentation and visual observation. Surface samples were taken along vessel transect paths prior to, during, and following each run in an attempt to determine where and how oil was displaced. A series of single location oil samples were acquired on all test days using portable "cookie cutter" samplers developed by GRSU researchers. Multiple location oil samples were taken on one date (February 21, 1978) using a strip sampler designed by CEL. Appendix A documents the surface sampling strategies employed during the course of the test program.

  The "cookie cutter" devices used in the program were designed to permit rapid sampling of oil slicks at single sampling points. They are relatively simple in design,

TABLE 1

FIELD DATA PRODUCTS COLLECTED DURING SEA CRUISES
(X-indicates data collected)

DATA TYPE	DATE OF SEA CRUISE 12/2/77	12/8/77	12/15/77	2/21/78
1. Photographic (Aerial)				
35mm Ektachrome		X	X	X
35mm Kodachrome	X	X		
35mm Kodacolor				X
35mm Ektachrome IR		X		X
Super 8mm Kodachrome	X	X		
16mm (USN)			X	X
2. Photographic (Surface)				
35mm Ektachrome			X	X
35mm Kodachrome	X	X	X	
35mm Kodacolor				
35mm Ektachrome IR	X	X		
Super 8mm Kodachrome	X	X	X	X
16mm (USN)				
3. Oil Sampling				
<u>Surface</u> -				
Cookie-cutter (single sample)	X	X	X	X
Strip (six samples)				X
<u>Subsurface</u> -				
Pump/Hose		X	X	
4. Oceanographic	X	X	X	X
5. Meteorological	X	X	X	X

consisting of a circular aluminum frame, approximately 15¼ inches in diameter, which houses a 3-M Inc. Type 156 oil sorbent pad (Figure 2). The pad is stretched across the frame prior to sampling operations and spring locked shut for quick release. The sampler is attached to an eight foot wooden pole using a chain bridle. Oil samples are obtained by lowering the "cookie cutter" into a slick for five to ten seconds. In principal, any oil present in the surface area cut by the sampler should adhere to the water repellent sorbent pad during the relatively short contact period. An aluminum lid, loosely fitted to the top of the sampler prevents spillover during sampling and insures that oil "captured" on the sorbent pad is from the "cut" area only. Following the dipping operation, the sorbent pad is removed from the aluminum frame and placed in a 32 oz. glass storage jar for analysis. Removal of a stained pad and its replacement with a clean pad takes from 45-60 seconds. From 30-45 surface samples were acquired during each test day using the "cookie cutters." A 21-foot Boston Whaler operated by UCSB's Marine Science Insititute (MSI) was used as a sampling platform (Figure 3).

The strip sampler was specifically designed to record oil thickness changes as they occurred from the hull of the cutter outward. The strip sampler consists of a rectangular aluminum frame approximately 8 feet long x 16 inches wide x 8 inches deep. Styrofoam floats secured to the frame provide positive buoyancy for the device. Six attachment stations for 3-M Type 156 oil sorbent pads are provided. The pads are attached to the strip sampler using machine screws and perforated aluminum sheeting. Wire mesh inserts secured to the midframe at each station prevent the pads from pulling loose when the sampler is placed in the water. Sampling was accomplished by lowering the device from the Coast Guard cutter using a rope bridle and the vessel's heavy duty winch (see Figure 4). The sampler entered the water perpendicular to the cutter's hull and contact between the sorbent pads and sea surface was maintained for approximately ten seconds as the buoyant sampler floated alongside the vessel. The strip sample was then pulled back onboard the cutter and the oil sorbent pads removed and stored.

Because of delays in fabricating the strip samplers, the devices were first sea tested on the December 15, 1977 cruise and were not operationally used until the final test day (February 21, 1978), where samples were obtained for two transects.

- Subsurface sampling -- This sampling method was developed in house by GRSU investigators to account for possible changes

in subsurface oil concentrations resulting from vessels operating through surface oil slicks. Basically, the sampling procedure involved taking water samples at one, three, five, and ten foot depths prior to and immediately following vessel runs. The major sampling was confined to within five feet of the surface, since it was assumed that most of the oil forced under by the shallow draft 82-foot cutters would remain within this narrow envelope. Samples also were taken at the four depths approximately two and five minutes after a cutter pass in an attempt to determine how long churned under oil would remain entrained in the water column. Appendix A provides detailed information on the sampling locations used during the two days (December 8 and 15, 1977) that subsurface sampling was conducted.*

UCSB Boston Whalers were used as sampling platforms on both dates. The sampling apparatus consisted of a hand-operated Gusher 10 pump, 25 feet of 1½ inch diameter flexible plastic hose, and an 18 foot long aluminum pole. The plastic hose was secured to the aluminum pole and connected to the pump. Subsurface samples were obtained by lowering the aluminum pole/hose combination to the desired sampling depth then drawing water up through the hose for capture in 32 oz. storage jars (Figure 5). A total of 36 subsurface samples were collected on December 8. A further 33 samples were acquired December 15 using this method.

2. Vessel Activity -- A variety of aerial and near surface photographic products were used to record oil displacement patterns created by vessels operating through oil slicks (see Section B.1 Oil Slicks for a description of photographic products acquired). Still and motion picture imagery was acquired prior to, during, and immediately after each vessel run through oil.

3. Oceanographic and Climatological Data -- Correlative oceanographic and meteorological data for each test day were compiled on station by GRSU and USCG personnel. These data included estimates of sea state, wave height/direction, wind speed/direction, current speed/direction, cloud cover, and visibility. In addition, CEL provided a wave rider buoy on several test days to record wave height in the test area.

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* Subsurface sampling was not attempted on February 21, 1978 due to the negative results obtained from laboratory analysis of the December 8, 1977 samples. See Section C.3 for details.

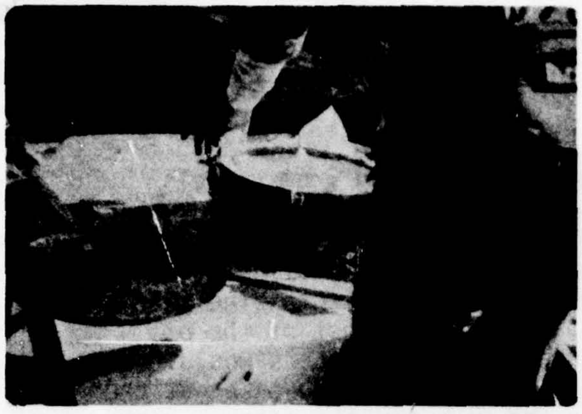

FIG. 2. "Cookie-Cutter" Oil Sampling Device

FIG. 3. Oil Sampling in Progress

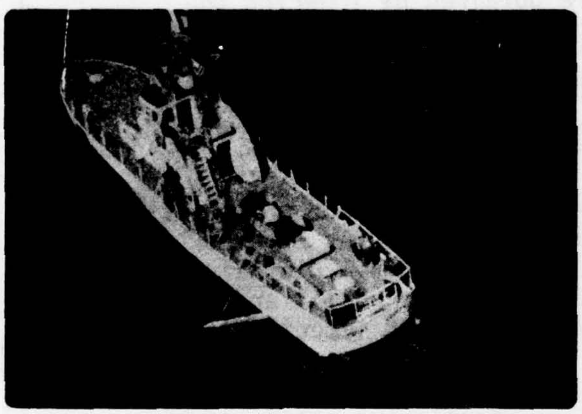

FIG. 4. Strip Sampler Being Lowered (Transect 1, 2/21/78)

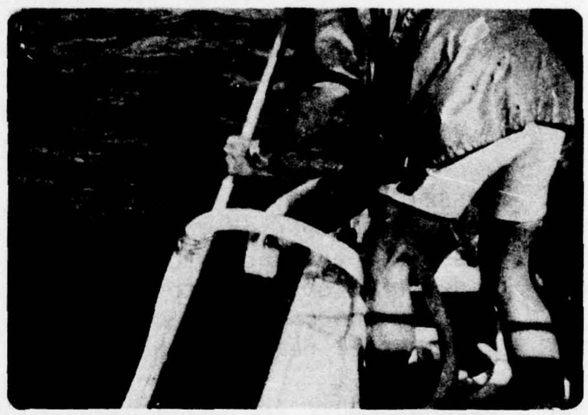

FIG. 5. Subsurface Sampling Operations

C. DATA PROCESSING AND REDUCTION

1. Photographic Products -- All 35mm and Super 8mm film products acquired by GRSU investigators during the program were processed commercially following each test. Duplicate copies of the 16 mm movies shot by CEL photographers for the December 15, 1977 and February 21, 1978 test were provided to GRSU by that organization's photo lab.

Upon receipt of the film products from the commercial processors, the Super 8mm movies and 35mm color negatives and color infrared slides were reviewed by the GRSU project manager for image quality and relevance of subject matter. Approximately 40 percent of the slides and negatives were judged to be of poor quality or of limited value for further analysis. These were removed from the active project file. In addition, four Super 8mm movies were found to be overexposed and were eliminated. The vast majority of the rejected 35mm slides and the four Super 8mm movies were from the December 2, 1977 test day. Considerable experimentation in exposure settings and shutter speeds was attempted on that date.

Following this initial review, the remaining photographic products were catalogued using the comprehensive photo logs maintained on each test day by observers onboard the Coast Guard cutters, UCSB whalers, and light aircraft and helicopters. All 35mm slides were directly annotated by date and transect number for ease of reference. The Super 8mm movies and 35mm negatives were similarly identified and catalogued. Once this had been accomplished, the film products were loaned to CEL for review and selective copying.

A second review of the imagery on hand was conducted once the data analysis phase was fully underway. This resulted in the elimination of nearly 50 percent of the remaining negatives and slides, thus allowing researchers to concentrate solely on those still film products which best documented surface oil conditions and vessel/oil slick interactions. The Super 8mm movies were also screened during the second review period to edit non-relevant or inferior quality footage.

2. Surface Sampling Results (Oil Thickness) -- Oil weight of each surface sample acquired on December 8, 1977; December 15, 1977; and, February 21, 1978 was determined using the gravimetric method. A total of 100 "cookie cutter" and 12 strip sampler surface samples were analyzed in this manner. The gravimetric method involved placing the oil soaked sorbent pads obtained at each sampling point in glass beakers, adding quanitites of solvent, agitating the solution, squeezing the sorbent dry, then repeating the solvent addition/extraction process a second time. The two solvent extracts were combined and treated with anhydrous sodium sulfate to remove entrained water. The solution was then boiled to evaporate the solvent and the weight of the residue oil was recorded to the nearest hundredth of a gram.

Most oil sampled had been on the surface for two hours or more and was virtually devoid of natural volatiles (see Section F.1.b. for a discussion of oil aging and loss of volatiles). Oil thickness for each sample point was determined by correlating oil weight with sorbent material surface area using a modified correlation equation developed by Mikolaj (1972).

Appendix B describes in detail the calibration and laboratory analysis procedures used in calculating oil thickness for the surface samples. Table B-1 lists oil film thickness results (in millimeters and inches) for the 112 surface samples analyzed.

3. Subsurface Sampling -- Laboratory analysis of 12 subsurface samples collected December 8 and 16 samples collected December 15 was completed by UCSB chemists in early January, 1978. These included samples taken at depths of one (1), three (3), five (5), and ten (10) feet at three locations. The basic procedure used in analyzing the samples was the gravimetric method described in Section C.2 (above). Laboratory analysis of subsurface samples gathered on the first two days proved negative (i.e., no oil was detected in any of the sample solutions). As a result, subsurface sampling was not attempted on February 21, 1978 and the remaining samples collected on December 8 and 15 were not analyzed. It has not been determined whether the absence of entrained oil in the samples was an artifact of the subsurface sampling program design or a true indicator that there was very little subsurface oil in the water column prior to or several minutes after passage of the cutters.

4. Oceanographic and Climatological Data -- Data on swell direction/height, wind direction/speed, current direction/speed, and visibility were compiled in tabular form on a daily basis (see Section B.3). This information was used to provide a reliable data base for determining the effects of natural conditions on oil slick surface patterns and for postulating potential meteorological and oceanographic-related impacts on vessel clean-up operations.

D. SEA TEST PROGRAM

A total of four sea cruises were conducted in the Santa Barbara Channel test site between December 2, 1977 and February 21, 1978. The U.S. Coast Guard provided 82-foot cutters based in Santa Barbara for each day's operations. These relatively shallow draft patrol boats were used to obtain data on the effects of typical "vessels-of-opportunity" on oil slicks. The cutter PT. EVANS completed four transects through oil on December 2 and three more on December 8. All seven runs were made at six knots or more. The cutter PT. HOBART made three runs on December 15 and the PT. JUDITH completed three additional transects on February 21. Two runs on each of those dates were conducted at speeds of five knots or less. Support vessels and aircraft associated with the test program included 21-foot Boston Whalers from UCSB and chartered light aircraft and Coast Guard helicopters.

Each test provided slightly different oceanographic, meteorological, and surface oil conditions. These ranged from near calm seas and medium-heavy natural oil slicks to moderate seas with waves cresting three to four feet and light-heavy oil. Unfortunately, no data were collected for sea state 4 and above conditions (i.e., winds of 17 knots plus with sea waves of eight feet or more). Failure to meet this pre-test objective of gathering data on vessel-oil interactions in rough weather and high seas was due to the nonavailability of U.S. Coast Guard cutters and/or extremely poor photographic and oil sampling conditions on the few days that these weather/oceanographic conditions existed during the eleven week sea test period.

Table 2 provides summary information for the December 2, 8, and 15, 1977 and February 21, 1978 sea cruises. This includes information on project participants; oil, meteorological,and oceanographic conditions in the test site; vessel headings and speeds for individual transects; and, general comments for each test day. Appendix C contains comprehensive descriptive data for each sea cruise.

TABLE 2 . TRANSECT SUMMARIES

Date	12/2/77	12/2/77	12/2/77	12/2/77	12/8/77	12/8/77	12/8/77
Transect #	1	2	3	4	1	2	3
Vessel Heading °	260	100	255	100	245	200	150
Vessel Speed kts.	6	6	6+	6+	6.2	6.6	6.4
Swell Height ft./Dir.°	2½-3/260	2½-3/260	2½-3/260	2½-3/260	1½-3/245	1½-3/245	1½-3/245
Wind Speed kts./Dir.°	4-6/220	4-6/220	4-6/220	4-6/220	5/150	5/150	5/150
Cloud Cover (%)	0	0	0	0	95	95	95
Visibility miles	Unlimited	Unlimited	Unlimited	Unlimited	1½-3	1½-3	1½-3
Oil Conditions (*)	Silver Sheen	Dull Irides-cence to Grey/Brown	Dull Iridescence	Silver Sheen to Iridescent	Dull Iridescence	Same as Transect 1	Same as Transect 1
Comments:	Cutter PT. EVANS used as test ship. This date was primarily dedicated to training project personnel and working out any "bugs" in the sampling plan.				Cutter PT. EVANS used as test ship. Oil conditions were excellent for the tests with large patches of medium to heavy oil. Surface and subsurface sampling were both undertaken.		

* at whaler

TABLE 2. TRANSECT SUMMARIES (cont.)

Date	12/15/77	12/15/77	12/15/77	2/21/78	2/21/78	2/21/78
Transect #	1	2	3	1	2	3
Vessel Heading °	255	075	270	275	175	235
Vessel Speed kts.	2.3	3.9	5	3.6	4.4	5.5
Swell Height ft./Dir.°	3-4/240	3-4/240	3-4/240	1-2/270	1-2/270	1-2/270
Wind Speed kts./Dir.°	15/210	15/210	15/210	3-5/200	3-5/200	3-5/200
Cloud Cover (%)	55	30	10	5-10	5	0
Visibility miles	10	10	Unlimited	8-10	10	15
Oil Conditions (*)	Rainbow Iridescence to Dull Iridescence	Same as Transect 1	Same as Transect 1	Dull Iridescence to Orange Jell	Same as Transect 1	Orange Jell to Chocolate Mousse
Comments:	Cutter PT. HOBART used as test vessel. Very choppy day with strong winds and whitecaps, sampling was difficult due to problems in keeping whaler stable. Swells dampened to 1½-2 feet in oiled areas.			Cutter PT. JUDITH used as test ship. Near calm seas and winds with scattered heavy concentrations of surface oil. No subsurface sampling attempted. Strip sampler used for first time.		

* at whaler

E. ANALYSIS OF VESSEL-OIL INTERACTIONS DURING INDIVIDUAL TRANSECTS

1. Background -- This section presents the results of our analysis of photographic, surface sampling, and field observation data for nine individual ship transects conducted through oil slicks in the Santa Barbara Channel on December 8 and 15, 1977 and February 21, 1978.* It should be emphasized that this section is primarily intended to document vessel-oil interactions and oceanographic/meteorological effects on vessel operations on a transect-by-transect basis, whereas Section F. provides general conclusions and a summary evaluation of the test program findings.

The primary data sources used to document the effects of surface vessels on oil slicks were still and motion picture photography and surface oil samples. Approximately 110 hours were spent reviewing representative 35mm slides and Super 8mm and 16mm movies for the three test days. Considerable attention was given to evaluating each run in terms of the interrelationships between vessel speed and direction, swell height and direction, wind speed and direction, and the resulting oil slick displacement patterns which could affect oil sorbent dispersion and recovery operations. Correlative aerial and near surface still and motion picture imagery proved especially useful for delineating the vessel-induced wave/wake patterns which displaced and broke up surface oil slicks. Oil film thickness surface samples taken prior to, during, and after each cutter run provided quantitative data for assessing vessel-related changes in slick configurations and supplemented the aerial and near surface imagery. These findings are documented in more detail in the following subsections which present results of our surface sampling program and describe the effects of vessels on oil slicks and oceanographic/meteorological factors on vessel operations for nine individual transects completed on December 8 and 15, 1977 and February 21, 1978. Unfortunately, the subsurface sampling program yielded negative results for entrained oil and no hard data were available for determining the amount of surface oil churned under and into the water column during each transect.

2. Oil Film Thickness Measurements (Surface Sampling) -- Surface sampling was conducted from UCSB whalers on December 8, December 15, and February 21 using the "cookie cutter" devices and from the USCG cutter PT. JUDITH on February 21 with the strip sampler. Table 3 summarizes the average oil thickness results for samples collected with the "cookie cutters" by date, transect, and location. Table 4 provides the same information for strip samples obtained on February 21. These tables are cited extensively in Section E.3, Analysis of Ship Transects which follows. Appendix A describes the sampling plan implemented for each date and illustrates the relative location of sampling stations to the surface vessels involved in the tests. Appendix B documents the laboratory procedures used to calibrate and analyze the oil samples and tabulates oil film thickness results for individual samples.

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* The four transects completed on December 2, 1977, the first test day, were not evaluted due to the nonavailability of adequate correlative photographic and surface sampling data sets for that date.

TABLE 3. OIL FILM THICKNESS MEASUREMENTS ("COOKIE-CUTTER SAMPLER)

	Average Oil Thickness (mm)				
Date/Transect #	Station A	Station B^1	Station B^2	Station C	Station D
12/08/77 (Transect 1)	0.069**	0.070*	0.068*	0.076**	0.047**
12/08/77 (Transect 2)	0.066**	0.068*	0.062*	0.068**	0.069**
12/08/77 (Transect 3)	0.068**	0.063*	0.063*	0.061**	0.064**
12/15/77 (Transect 1)	0.084**	0.208*	0.262*	0.106**	0.069*
12/15/77 (Transect 2)	0.057**	0.026*	0.058*	0.043**	0.060**
12/15/77 (Transect 3)	0.052**	0.056*	0.044*	0.051**	0.038**
02/21/78 (Transect 1)	0.112**	0.118*	0.121*	0.088**	-
02/21/78 (Transect 2)	0.071**	0.068*	0.068*	0.082**	-
02/21/78 (Transect 3)	0.153**	0.115*	0.103*	0.139**	-

Locations:
Station A - In path of cutter (before pass)
Station B^1 - Off path of cutter (on crest of bow wave)
Station B^2 - Off path of cutter (in following trough)
Station C - In wake of cutter (after pass)
Station D - Off path of cutter

* Based on one sample
** Based on three samples
*** Based on four samples

TABLE 4 . OIL FILM THICKNESS MEASUREMENTS*
(Strip Sampler, USCGC PT. JUDITH, 2/21/78)

Station	Oil Thickness(mm)	
	Transect 1	Transect 2
1. 12-28" from cutter	0.199	0.156
2. 28-44" from cutter	0.137	0.109
3. 44-60" from cutter	0.125	0.120
4. 60-76" from cutter	0.200	0.096
5. 76-92" from cutter	0.138	0.078
6. 92-108" from cutter	0.121	0.074

* Based on one sample per station

Operation of the "cookie cutter" and strip samplers went relatively smoothly under environmental conditions experienced during the program. Minor problems in sampling with the "cookie cutters" were encountered, however, on December 15. Operators found that changing the sampling pads was difficult due to the high wind conditions and that they often had to drag the samplers through the water to maintain contact between the oil film and sorbent pads. These problems are reflected in the results for Transects 1 and 2 (see Table 3).

Disregarding oceanographic and meteorological effects, the major difficulty experienced when collecting surface samples with both the "cookie cutter" and strip samplers was operator bias. For example, at any given sampling location there was always enough variability in oil film thickness within the eight foot reach of the "cookie cutter" that an operator could easily collect several samples that might vary by up to 150 percent (see Appendix B, Table B-1). Consequently, even though the sampling boat itself might appear to be in the middle of an oil slick with uniform surface thickness characteristics, the measured thickness of a sample might bear little relation to the average thickness in the immediate vicinity. To counteract this problem, multiple samples were obtained and averaged when possible. Sampling crews also carefully observed and annotated apparent oil film color in each sampling location to provide a correlative data source.

Similar problems faced personnel involved in strip sampling, since there normally was considerable variability in oil film thickness along a transect and the device, because of its bulky nature, could not be lowered accurately to a precise sampling location. In addition, the strip sampler did not come out of the water cleanly during one transect and momentary dragging may have resulted in slightly spurious oil thickness data for the first run.

A cursory review of the oil film thickness readings obtained from the "cookie cutter" and strip samples (Tables 3 and 4), and examination of photographic imagery, provided evidence that:

- Redistribution of oil by the bow and stern waves through turning under and/or pushing out is relatively short term. Most of the affected oil can be observed resurfacing along the hull. When bow waves do not break, surface oil slicks normally stretch out but remain intact as the wave passes under.

- There is little piling up of oil evident at the interface between the breaking bow waves and undisturbed surface slicks (compare readings for Stations A, B-1, and B-2 in Table 3). When oil does pile up, it appears to be confined to very narrow swaths approximately two to six inches wide. This was observed both on film and by investigators on the whalers.

- Oil concentrations are thickest immediately adjacent to the cutter hull (i.e., within 0-28 inches), with oil thickness decreasing at a variable rate outward (Table 4). This would seem to indicate that surface oil displaced by the cutter's bow is piling up on undisturbed oil immediately adjacent to the hull, as a ship proceeds through a slick.

- Turbulent stern wake areas, while appearing to be relatively free of oil on photographic imagery (and to the naked eye), actually contain significant concentrations of surface oil. Sampling for all three days showed average oil thickness concentrations in the wake to be within thirty percent of the surface oil concentrations prior to a cutter pass (compare readings for Stations A and C in Table 3).

- These general findings appeared to be relatively independent of vessel speed/direction and environmental conditions encountered during the tests.

3. Analysis of Individual Ship Transects (December 8, 1977; December 15, 1977; and February 21, 1978) -- During our analysis of the transect data, it became apparent that vessel speed was the most significant factor affecting vessel-oil interactions. Oil film thickness, swell height/direction, wind speed/direction and other oceanographic and meteorological forces were of secondary impact. Furthermore, noticeable differences in the formation of primary and secondary bow and stern waves, which turned under and/or pushed out surface oil, were observed as the cutters operated at different speeds. For example, at the lower speeds (i.e., three knots and less) oil slicks would generally run undisturbed alongside the cutter's hull and provide an excellent target for recovery by sorbent chips. As ship speeds increased, the slicks were frequently disrupted by breaking bow and stern waves which churned oil under near the bow and forced remaining surface oil approximately three to five feet away from the hull. This action also created a zone of turbulence alongside the hull where oil alternately resurfaced and then submerged. At speeds of 5 knots or more, and occasionally at lower speeds, oil also was pushed away from the cutters by waves that formed off the stern. Finally, regardless of operating speeds, the cutters consistently left a stern wake that appeared clear of oil on photographic imagery and to observers onboard the test vessels. Surprisingly, comparison of laboratory results of the oil film thickness measurements taken in the path of the cutter before it passed the sampling boat and in the wake of the cutter following a pass showed little variation in surface oil concentrations despite the different reflectance characteristics.

The individual transect assessments are grouped according to the average ship speed maintained throughout a run to reflect the importance of that driver in vessel-oil slick interactions. The following categories are used:

- Low Speed Runs (three knots and less) - one run each from December 15 and February 21.

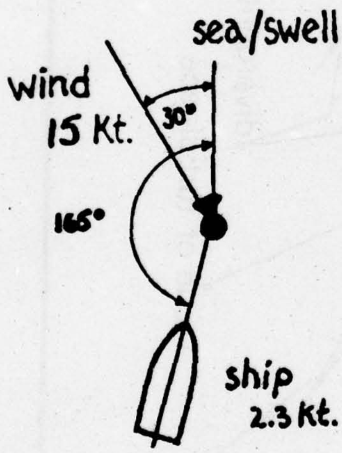
- Middle Speed Runs (three to six knots) - two runs from both December 15 and February 21.

- High Speed Runs (six knots and above) - three runs from December 8.

Each transect analysis has a heading diagram which plots the ship course in relation to swell and wind direction. Figure 6 shows the general location of the bow waves (primary and secondary), stern wave, and hull and wake turbulence zones typically generated by the cutters during the sea tests.

a. Low Speed Runs (three knots and less)

- December 15, 1977 - TRANSECT 1 (Vessel Speed, 2.3 knots; Swell Height, 3-4 feet; Wind Speed, 10-15 knots)



Observed effects of the cutter on oil: The vessel heading on this run was 255° magnetic at a speed of 2.3 knots. This heading was slightly to starboard of running directly into the swell. Wind was off the port bow from 210°. The oil was predominantly grey/brown with intermittent areas of thinner rainbow coloration. Due to the choppy sea state, small breaks in the continuous slick were seen through out the day.

During this transect, the PT. HOBART produced little or no bow or stern wave action. This seemed to be due in part to the very slow vessel speed. The cutter traveling through the swells created little observable effect on the surface oil. The oil was observed travelling along the hull from bow to stern (Figure 7). Occasional small non-breaking bow waves were produced by vessel pitch but had little effect on the surface oil. The stern wake exhibited a reflectance variation from the surrounding slick simulating the absence of oil. The width of the observed wake was approximately 15-20 feet. Three surface samples taken in the wake area showed an average oil film thickness of 0.106mm (0.004 in.) compared to 0.084mm (0.003 in.) recorded in the same area prior to the vessel pass (Table 3, Stations A and C). The higher values found in the wake area after the

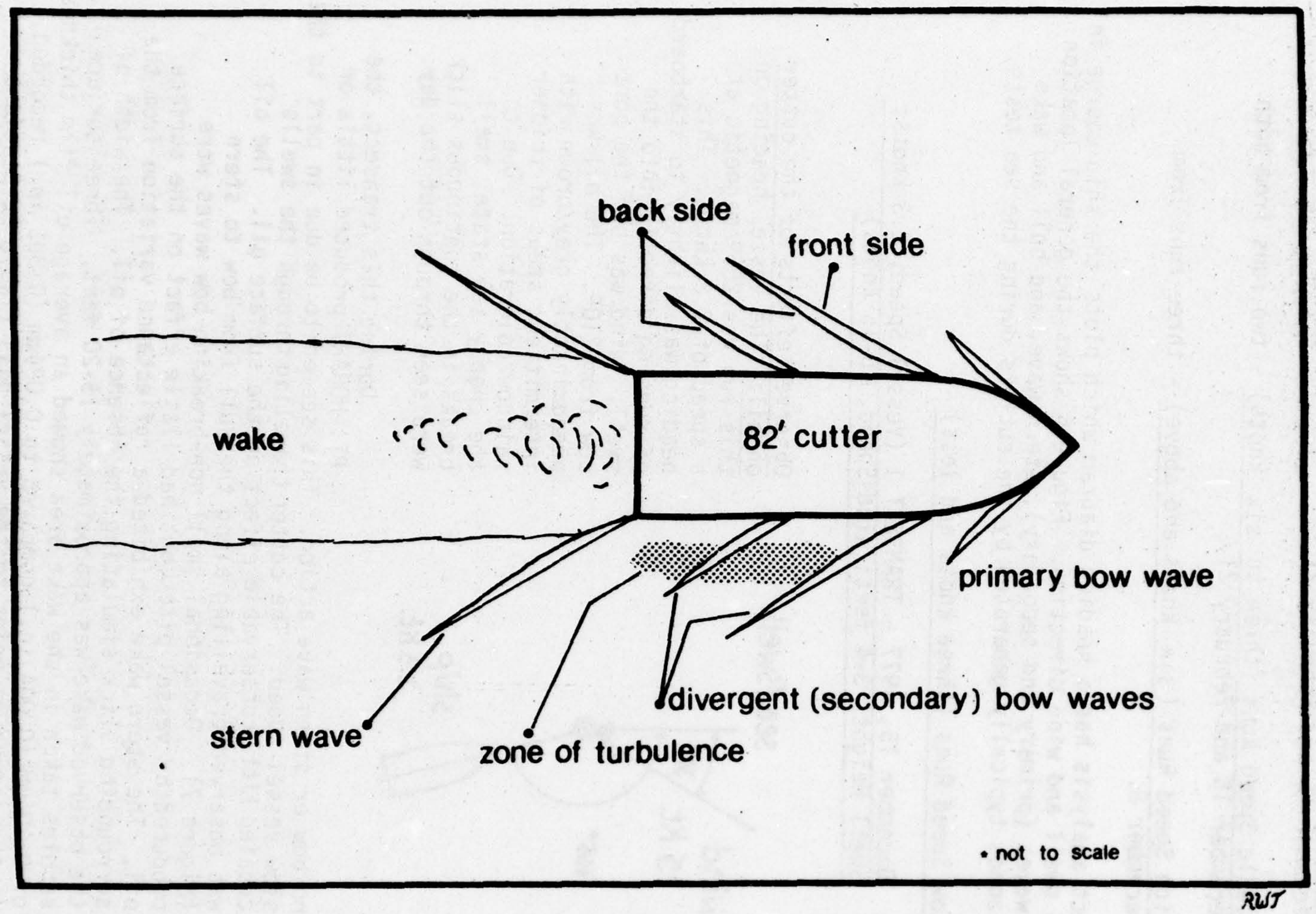
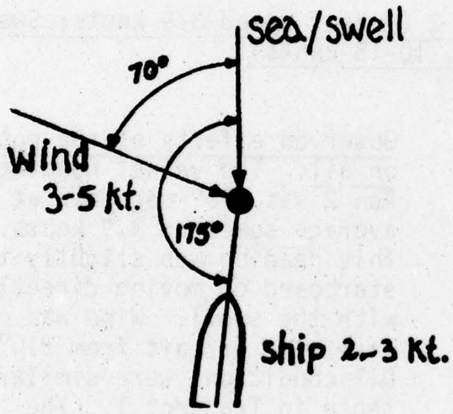


FIG. 6. Characteristic Wave Patterns Generated by 82-Foot Patrol Cutters

cutter pass may be attributed to additional oil being blown and/or carried into the turbulent zone by 15 knot winds and high swell.

Effects of ocean/weather conditions on ship operations: The relatively rough seas produced substantial vessel pitch and roll. Portions of the bottom of the hull were exposed as the swell trough moved along it (Figure 8). However, there was no "splash out" of surface water.

- February 21, 1978 - TRANSECT 1 (Vessel Speed, 2-3 knots; Swell Height, 1-2 feet; Wind Speed, 3-5 knots).



Observed effects of the vessel on oil: This run was steered into the swell on a course of 275° magnetic. The PT. JUDITH's speed was 2-3 knots with wind off the port bow from 200° magnetic. The dominant oil type was a thick brown, water in oil emulsion of "chocolate mousse" concentrated into long narrow "windrow" streamers. Thinner contiguous to non-contiguous oil slicks also existed in conjunction with the brown streamers. Surface cover of oil varied from 30-100%.

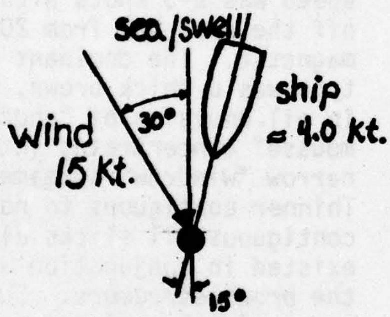
The cutter had little apparent effect on surface oil during this run. The poorly develcped bow and stern waves showed no signs of breaking or spilling whitewater during the entire run. The medium thick oil slicks which were traversed remained in a cohesive form at all times when the low waves passed under them. While the bow waves caused the surface oil film to stretch when a wave crest passed beneath, no oil breakup occurred during this run. Oil remained in a cohesive state alongside the vessel until it reached the stern. At that location turbulence and eddies associated with the stern wake caused some oil to be broken up and pulled into the stern area. This was a fairly random occurrence and as such the amount of oil visible on the surface within the stern wake was quite variable. The remainder of the oil was piled up at the oil slick/boat wake interface (Figure 4). This oil was slowly pulled into the wake within a minute or two after the cutter passed. The average surface oil film thickness at the pretransect sampling location was 0.112mm (0.004 in.). Following the cutter transect, oil thickness in the wake was 0.088mm (0.003 in.). See Table 3, Stations A and C.

With the mild seas, low speed and thick cohesive oil, little turning under or pushing out of surface oil occurred other than the actual displacement of oil by the vessel's hull. Sampling from the cutter using the six station strip sampler tended to confirm this observation with the heaviest oil concentrations piling up within six feet of the hull (Table 4, Transect 1). Highest oil thickness readings were near the hull/oil interface, 0.149mm (0.006 in.), and five to six feet out at the edge of the weak boundary layer zone, 0.200mm (0.008 in.).

Observed effects of ocean/weather conditions on ship operations: Conditions were very mild producing minimal effects on the vessel.

b. Middle Speed Runs (three to six knots)

- December 15, 1977 - TRANSECT 2 (Vessel Speed 3.9 knots; Swell Height, 3-4 feet; Wind Speed, 10-15 knots)



Observed effects of the cutter on oil: The vessel heading on Run 2 was 075° magnetic at an average speed of 3.9 knots. This heading was slightly to starboard of moving directly with the swell. Wind was off starboard and aft from 210°. Oil conditions were similar to those in Transect 1. The dominant oil color was grey/brown with patches of rainbow.

During this transect slight nonbreaking bow waves were produced. Oil was observed passing over and down the waves as they moved along the surface (Figure 9). In most cases, the oil slick would seem to stretch as the wave moved through it and contract after the wave had passed. Water along the hull of the vessel exhibited slight eddy motion at times but had little effect on the surface oil beyond causing it to swirl slightly. Oil was seen in many instances passing directly along the hull from bow to stern (Figure 10). The stern wake exhibited a reflectance pattern which seemed devoid of oil as in the first transect. Surface samples taken prior to the vessel passage and after passage in wake area show little change in surface oil magnitude. The average oil film thickness prior to vessel passage was 0.057mm (0.002 in.) versus 0.043mm (0.002 in) after the pass (Table 3, Stations A and C).

FIG. 7. Oil Travelling Along Hull
(Transect 1, 12/15/77)

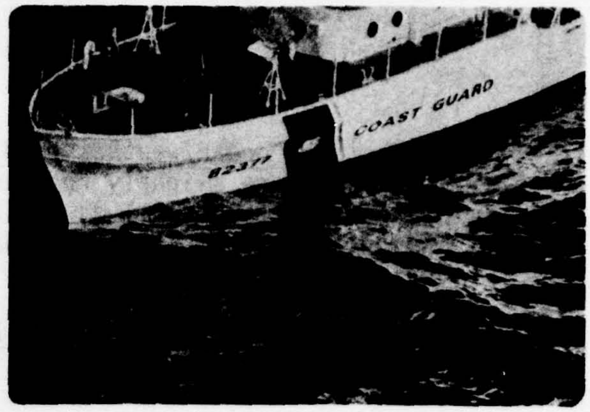


FIG. 8. Sea Swell Along Cutter Hull
(Transect 1, 12/15/77)

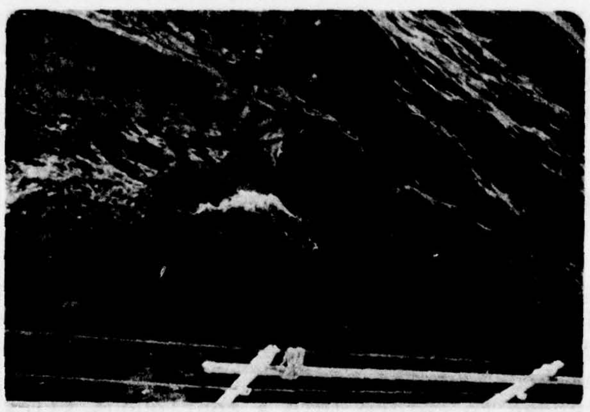
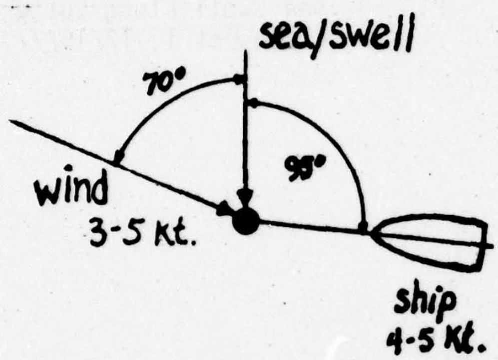


FIG. 9. Oil Adjacent to Cutter Hull
(Transect 2, 12/15/77)

Effects of ocean/weather conditions on ship operations: Pitch and roll were slightly reduced during the transect. Swell waves passed along the hull as in Transect 1 but the bottom of the hull was not exposed (Figure 11) and no "splash out" of water was observed.

- February 21, 1978 - TRANSECT 2 (Vessel Speed, 4.4 knots; Swell Height, 1-2 feet; Wind Speed, 3-5 knots)



Observed effects of the cutter on oil: This second transect was run nearly perpendicular to the swell on a course of 175° magnetic. The vessel speed was 4.4 knots and the wind was off the starboard bow. Surface oil was observed to be very old and tarry with dust and broken kelp fronds mixed. Color was "chocolate mousse" to orange jell.

During this transect, bow and stern waves formed as ship speed reached four knots. At times, the primary bow wave, first and second divergent bow waves, and stern wave were observed breaking. This run provided good evidence of the wave dampening effects of oil. Where there was thick emulsified oil, surface tension tended to dampen the breaking bow and stern waves (Figure 12). When the cutter passed through thick oil into areas of thinner oil, the dampening effect was reduced and the vessel-induced waves began to break and show whitewater (Figure 13).

Bow and stern wave turbulence was apparent even under non-breaking conditions. Small zones of turbulent water were observed on the backside of the primary and divergent bow waves. This turbulent water broke up the surface oil as the wave passed. The oil then tended to reform into a contiguous slick almost immediately. When whitewater did occur on the bow and stern waves, a minimal amount of outward displacement was observed with oil riding over or around turbulent water zones associated with bow and stern waves.

Boundary layer turbulence was observed adjacent to the cutter's hull. This zone of disturbance was approximately two feet wide near amidships but narrowed to approximately one foot at the stern. The turbulent water tended to break up surface oil, which was momentarily churned under then resurfaced along the hull or was pushed out along the frontside of the boundary

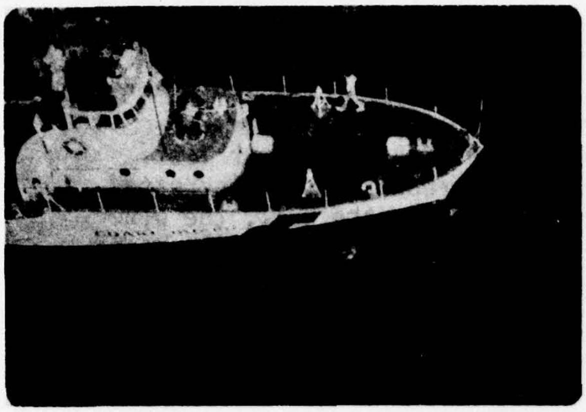


FIG. 10. Aerial View of PT. HOBART Showing Oil Travelling Along Hull (Transect 2, 12/15/77)

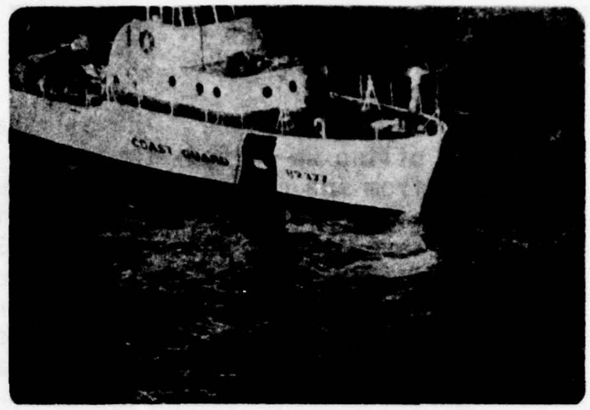


FIG. 11. PT. HOBART Proceeding with Swell (Transect 2, 12/15/77)

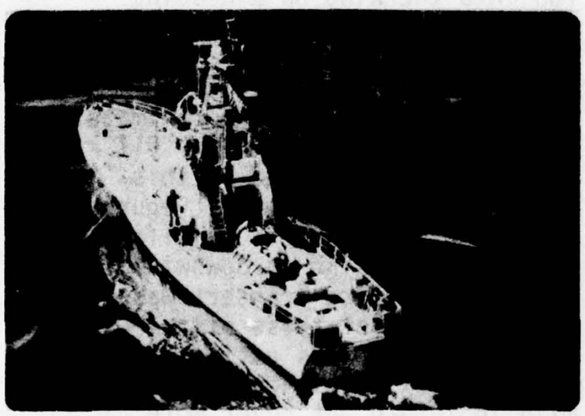


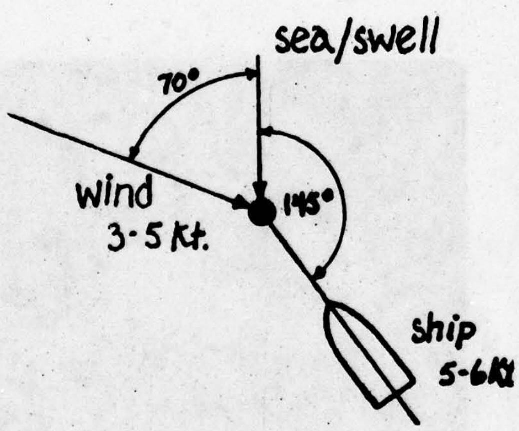
FIG. 12. Heavy Oil Dampening Bow Waves (Transect 2, 2/21/78)

FIG. 13. Breaking Bow Waves in Thinner Oil (Transect 2, 2/21/78)

layer interface. The oil that was pushed out, was observed piling up on undisturbed oil approximately three to four feet from the cutter. Thus, there were two narrow zones of increased oil concentration evident this run; one along the hull, the other several feet out (see Table 3, Stations A and C). As in Transect 1 (2/21/78), patches of intact, heavy crude oil were observed floating in the stern wake area immediately after the cutter passed. Failure of the cutter-induced stern waves and wake action to break up the oil was due to the tarry nature of the oil.

Effects of ocean/weather conditions on ship operations: These were minimal on this run. Due to the direction steered, roll of the vessel was more pronounced but had little to no effect on bow/stern wave frequency and height. Vessel speed was the primary factor affecting wave formation.

- February 21, 1978 - TRANSECT 3 (Vessel Speed, 5-6 knots; Swell Height, 1-2 feet; Wind Speed, 3-5 knots)



Observed effects of cutter on oil: The PT. JUDITH made the third run into the wind on a heading of 235° magnetic. Vessel speed was five to six knots, with an average speed of 5.5 knots. Swell was coming from approximately 35° off the starboard bow. Oil conditions encountered on this run were extremely heavy (Figure 14) with long windrows of emulsified tarry crude lining up downwind. Much of the third transect was run along one of these oil windrows, which was estimated to be approximately one-half mile in length but never more than thirty yards wide.

During this run bow and stern waves began forming as the cutter passed through three knots. These irregular waves became more frequent and well developed as the PT. JUDITH reached a cruising speed of five knots. The breaking bow waves extended approximately eight to ten feet from the cutter's hull, in contrast to the estimated distance of five to seven feet observed during Transect 2 on February 21. This increase in surface area affected by wave action was due to the formation of a third bow wave behind the primary and secondary (divergent) waves (Figure 15). The occurrence of multiple bow waves (primary and divergent) was noted on all runs made at five knots or more.

Little outward displacement or churning under of oil by bow wave action was observed. Instead, most of the very thick crude oil cut by the PT. JUDITH rode down the backside of breaking bow waves (Figure 16), or merely slid along the hull when the bow waves were not breaking. In the latter instance, the slick remained intact and relatively undisturbed. Oil pushed aside by the bow probably piled up on undisturbed surface oil adjacent to the hull, although this displacement could not be confirmed due to the absence of strip sampler data for the run. More research is required to establish whether this apparent displacement of oil actually occurs.

When the bow waves were breaking, surface slicks within the affectd areas also remained near contiguous and unbroken except in small zones of turbulence located on the backside of the divergent waves. These turbulent zones occurred approximately four to six feet out from and parallel to the cutter's hull (Figure 17). Oil could be seen resurfacing almost immediately as the turbulent water lost energy. This would seem to indicate that oil entrainment was relatively shallow (e.g., probably no more than two or four inches below the surface). As noted above, little surface oil was observed being displaced outward (and piled up on undisturbed oil) by the front crest of the breaking bow waves. Samples taken on the crest and trough of the bow waves tended to verify this conclusion. Oil film thickness readings at these locations were somewhat lower than those obtained in undisturbed oil prior to the cutter's passage (Table 3, Stations A, B-1, and B-2).

When the oil reached the stern area, it was affected by turbulence from the stern wave and small eddies forming adjacent to the hull and parallel to the propellers. Again, there was little clearing of oil away from the hull, with most of the oil either being piled up at the wake turbulence/undisturbed oil interface or pulled under and into the wake area. However, some oil also was observed on the surface sliding behind the stern and into the wake where it remained intact (Figure 18). This latter process appeared to be a random one, depending on vessel speed (five or six knots), status of the propeller (engaged or disengaged), thickness of oil, and general boat oscillations. Average oil thickness in the wake two minutes after the cutter passed was 0.139mm (0.005 in.) compared with 0.153mm (0.006 in.) for the same area just prior to the PT. JUDITH's pass (Table 3, Stations A and C).

Effects of ocean/weather conditions on ship operations: Once again, the extremely calm seas and favorable winds had no effect on vessel operations in terms of potential ability to disperse and recover oil sorbent chips.

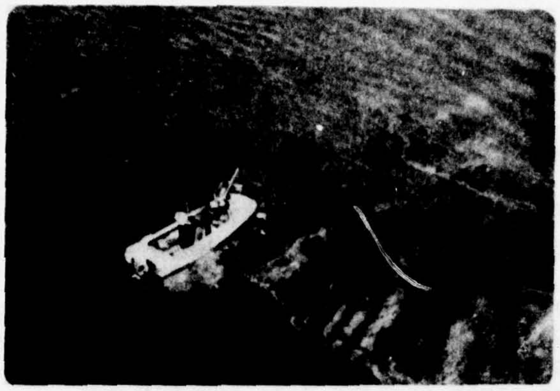


FIG. 14. Heavy Surface Oil (Transect 3, 2/21/78)

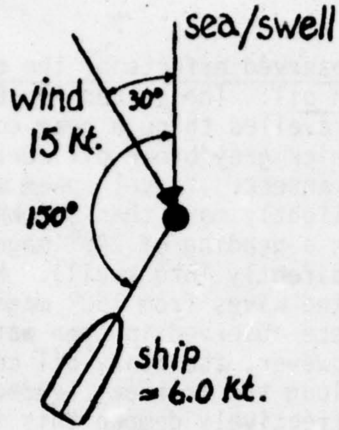
FIG. 15. Multiple Secondary Bow Waves From PT. JUDITH During 5-Knot Run (Transect 3, 2/21/78)

FIG. 16. Thick Crude Riding Backside of Bow Waves (Transect 3, 2/21/78)

FIG. 17. Zones of Turbulence Off PT. JUDITH (Transect 3, 2/21/78)

FIG. 18. Oil Sliding into Stern Wake (Transect 3, 2/21/78)

- <u>December 15, 1977 - TRANSECT 3 (Vessel Speed 5.0 knots; Swell Height, 3-4 feet; Wind Speed, 10-15 knots)</u>



<u>Observed effects of cutter on oil</u>: The vessel heading on this run was 270° magnetic at a speed of 5.0 knots. This heading was 30° to starboard from the oncoming swell. Wind was off the port bow from 210° . The dominant oil color was grey/brown with patches of rainbow.

During this transect, large primary bow waves, divergent bow waves and stern waves were produced. Vessel pitch and roll increased substantially. These conditions were attributed to increased speed and the ship's heading into the swell.

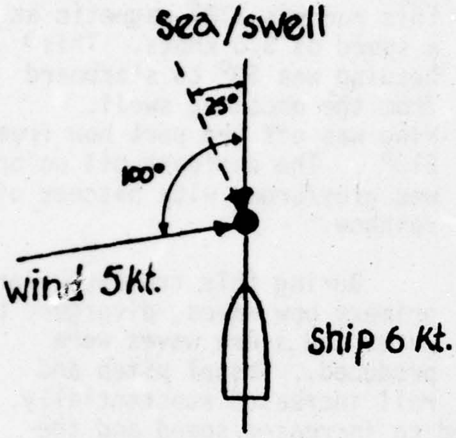
Surface oil accumulations alongside the hull were broken substantially by the large "splash out" type bow waves (Figure 19). Oil was pushed out and considerable mixing and submergence occurred under these oceanographic conditions. Quantities of oil were seen in the turbulent water produced by breaking bow waves, with lesser amounts visible sliding down the backs of these waves.

Accumulations of oil were observed resurfacing along the hull of the cutter, mainly along the after half. This oil was in a non-continuous state and quantity decreased as bow wave frequency and amplititude increased. Average oil film thickness measurements before and after the run, however, showed little variation in oil quantities. Average oil film thickness prior to vessel passage was 0.052mm (0.002 in.) versus 0.043mm (0.002 in.) after (Table 3, Stations A and C).

<u>Effects of ocean/weather conditions on ship operations</u>: At this heading and speed, the cutter hull was observed lifting out of the water, crashing into the swell waves, and splashing out water in large amounts (Figure 20). The occurrence of these "splash out" waves was dependent upon swell size, frequency, and direction and hull angle.

c. High Speed Runs (six knots or more)

- December 8, 1977 - TRANSECT 1 (Vessel Speed, 6.2 knots; Swell Height, 1½-3 feet; Wind Speed, 5 knots)



Observed effects of the cutter on oil: The cutter PT. EVANS travelled through near continuous thick grey/brown oil during this transect. Vessel speed was slightly more than six knots on a heading of 245° magnetic (directly into swell). Minor wind waves from 150° magnetic were observed in open water. However, the heavy oil cover along the transect tended to effectively dampen this influence.

Throughout the run, the PT. EVANS created well defined primary and divergent bow and stern waves (Figure 21). These were attributed to the cutter speed. When the bow waves were breaking, undisturbed surface oil on the wave crests was observed being churned under or pushed out away from the cutter. This was especially apparent in the whitewater areas created by the divergent (secondary) bow waves and the resulting zone of turbulence created between the ship and the wave crest (Figure 22). Oil displacement was very regular both to starboard and port of this heading into the swell.

Much of the oil that was churned under by the primary and divergent bow waves appeared to resurface in the zone of turbulence opposite the bridge of the cutter within three to five seconds. From this point the oil in suspension typically reformed into semi-continuous slicks and continued down the hull to just forward of the stern. The resurfacing oil was also joined in many instances by undisturbed surface oil sweeping in toward the hull from behind the dissipating divergent waves (Figure 23). and lesser concentrations of oil that had been pushed out on the frontside of the divergent waves. These latter concentrations often appeared to pile up in narrow two to three inch wide strips on undisturbed oil as the bow waves dissipated. However, sampling on the crest and trough of the bow waves (Table 3, Stations B-1 and B-2) showed no evidence of significant changes in oil film thickness at the interface.

The combined slicks resulting from these two sources were once again disrupted in the stern area by a low, frequently

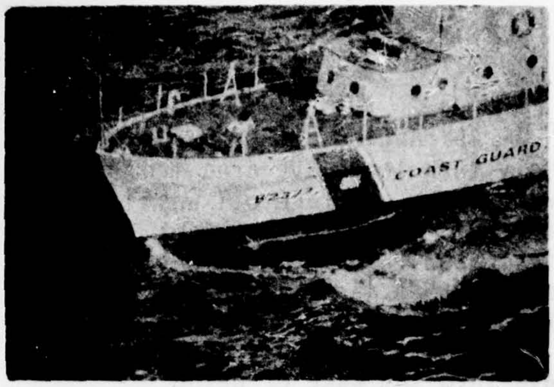


FIG. 19. PT. HOBART Creating "Splash Out" (Transect 3, 12/15/77)

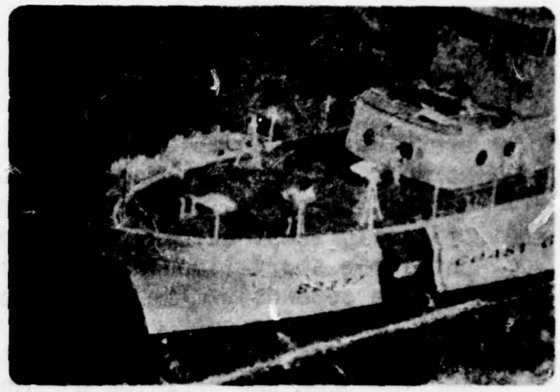


FIG. 20. PT. HOBART Lifting Out of Water During Run into Swell (Transect 3, 12/15/77)

FIG. 21. PT. EVANS Underway at 6-Knots Showing Well Developed Bow Waves (Transect 1, 12/8/77)

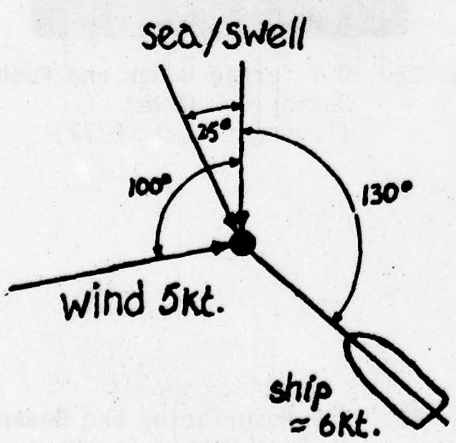
FIG. 22. Oil Turned Under and Pushed Out by Bow Waves (Transect 1, 12/8/77)

FIG. 23. Oil Resurfacing and Sweeping in From Behind Bow Wave (Transect 1, 12/8/77)

breaking wave which extended at 30° - 45° angles out from both corners of the stern and the extremely turbulent wave area from aft of the stern. When the stern wave broke, surface oil was primarily swept out and away from the hull three to five feet until the short-lived wave crest dissipated (usually within three to five seconds). The oil pushed out in this manner then sloshed back toward the cutter wake and mixed in this zone of turbulence. Oil that was not tranported on the stern wave crest was observed surfing down the backside of the wave into the wake or being sucked under the hull near the stern and (presumably) mixed into the water column by propeller-action. The wake appeared to be clear of oil across a zone of turbulence approximately 20-25 feet wide following passage of the cutter. However, three surface samples obtained in the wave within two minutes of the transiting cutter (Table 3, Stations A and C) showed an average oil film thickness of 0.076mm (0.003 in.) compared to a pretransect surface film thickness of 0.069mm (0.003 in.). This would seem to indicate that most of the oil displaced by the cutter had resurfaced in the wake area within this relatively short time.

Effects of ocean/weather conditions on ship operations: Oceanographic and meteorological conditions had little impact on vessel operations during this transect. While bow waves were frequent at six knots, there was no lifting of the bow out of the water. The cutter cruised smoothly on a course directly into the regular 1½-3 foot high swells. Mild five knot winds across the vessel from port to starboard also had no noticeable effect.

- December 8, 1977 - TRANSECT 2 (Vessel Speed, 6.6 knots; Swell Height, 1½-3 feet; Wind Speed, 5 knots)



Observed effects of the cutter on oil: The PT. EVANS completed the second run through surface oil conditions similar to those encountered during Transect 1. Oil color was predominantly a grey/brown with spotty concentrations of thinner rainbow tinged oil and occasional patches of very thick, dull brown to chocolate colored crude. Vessel speed averaged 6.6 knots. The transect was run slightly across swell on a heading of 200° magnetic. The wind was from 150° and across the cutter's bow from port to starboard.

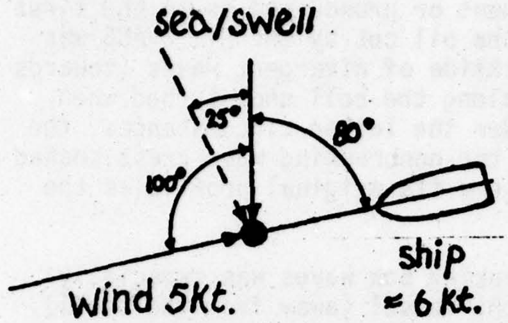
Aqain the secondary bow waves and smaller stern waves were primarily responsible for displacement of surface oil. Although there was churning under and pushing out of oil on this run, it was not as frequent or pronounced as on the first transect. Instead, much of the oil cut by the PT. EVANS was observed running down the backside of divergent waves (towards the hull) or merely sliding along the hull undisturbed when the waves did not break. Under the latter circumstances, the surface oil would stretch as the nonbreaking wave crest snaked away from the cutter then resume its original profile as the cutter passed (Figure 24).

The occurrence of nonbreaking bow waves was especially evident on the port side of the vessel (away from the swell). Even when the bow wave did break, oil on the portside was observed resurfacing almost immediately to form large patches of oil which continued aft approximately one to two feet out from the hull. The divergent (secondary) bow waves broke more regularly to starboard under the influence of the converging swell and often cleared an area approximately 10-15 feet wide from amidships to the stern. While some of the displaced oil was observed riding onto undisturbed oil, sampling on the crest and trough of the divergent bow wave showed little difference in thickness characteristics from the samples taken before the cuttter passed (Table 3, Stations A, B-1 and B-2).

Most of the surface oil approaching the stern appeared to be pushed out three to five feet from the wake by the stern waves, with the remaining oil surfing down the backside of the stern wave into the wake or sucked under the hull. The stern wake was an estimated 20-25 feet wide on this run or approximately 1½ times the width of the cutter (Figure 25). Three surface samples taken in the zone of wake turbulence showed an average oil film thickness of 0.068mm (0.003 in.) versus 0.066mm (0.003 in.) recorded in the same area prior to the cutter pass (Table 3, Stations A and C).

<u>Effects of ocean/weather conditions on ship operations</u>: Swell direction had a definite effect on the oil displacement patterns created by the PT. EVANS during this run. Oil to the port side of the cutter (sheltered from the swell) was little affected, primarily because the bow and stern waves broke irregularly. Conversely, the ship generated waves frequently broke and churned oil under or sloshed it out and away from the cutter to starboard, where radiating bow and stern waves crossed the swell at an angle. The PT. EVANS exhibited no swell-induced pitch or roll characteristics during this run. Wind had little effect on vessel operations since the heavy surface oil dampened wind waves within the slick.

• December 8, 1977 - TRANSECT 3 (Vessel Speed, 6.4 knots; Swell Height, 1½-3 feet; Wind Speed, 6 knots)



Observed effects of the cutter on oil: The cutter PT. EVANS steered the third transect through thick grey/brown oil. The heaviest oil was encountered opposite the sampling boat. The run was made at 6.4 knots average speed on a heading of 150° magnetic. This took the vessel directly into the wind and down the trough of the swell which was from 245° magnetic.

Primary and secondary vessel-induced waves were well developed and consistent this run. This was especially evident to the starboard side of the cutter where the divergent bow waves rose rapidly before being cancelled by the oncoming swell. Ship generated waves to the sheltered portside were smaller and more regular. During initial formation the divergent (secondary) bow waves to the starboard pushed surface oil away from the hull. There also was a great deal of whitewater on the breaking wave crests which caused considerable mixing of entrained surface oil into the water column. Surprisingly, large patches of oil (i.e., up to three feet wide) were observed surfing down the backside of these bow waves between areas of whitewater (Figure 26). This oil then rode on the surface and along the side of the hull toward the stern. Additional oil was sloshed back toward the cutter by the oncoming sea swell which overrode the bow waves and forced oil on the wave crests into the ship's boundary layer area. As a result, oil covered much of the sea surface adjacent to the cutter (from amidships to the stern). The only exceptions to this pattern were areas of turbulence created at the interface between the breaking bow waves and the oncoming swell (Figure 27).

In low sea state conditions, where the swell would not create excessive pitch and roll effects, the trough facing the oncoming swell would appear to be a prime area for dispersal of sorbent material due to the regular concentrations of surface oil. Results of surface sampling conducted before the cutter passed and on the bow wave crest and trough showed little variation in oil film thickness (Table 3, Station A, B-1 and B-2). This would seem to indicate that significant amounts of surface oil were not carried on the frontside of the bow waves.

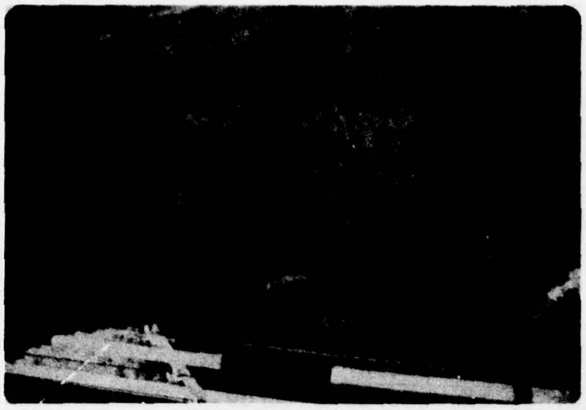


FIG. 24. Surface Oil Stretching as Non-breaking Biw Wave Passes (Transect 2, 12/8/77)

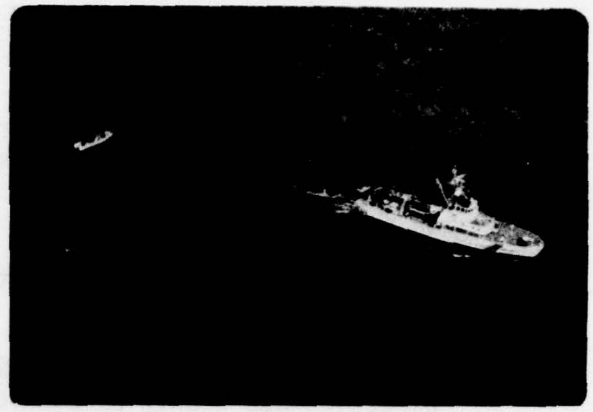


FIG. 25. Stern Wake Formed at 6-Knots (Transect 2, 12/8/77)

FIG. 26. Oil Surfacing Down Backside of Bow Wave (Transect 3, 12/8/77)

FIG. 27. Zone of Turbulence (Transect 3, 12/8/77)

Once the oil reached the stern area it was pushed out by the stern wave or pulled under the hull. Very little oil was observed surfing down the backside of the wave. Sampling indicated that there was only a 0.007mm (0.0003 in.) difference in surface oil concentrations before and after the cutter passed the whaler (Table 3, Stations A and C), a finding consistent with oil film thickness results from the other two transects run on December 8.

Effects of ocean/weather conditions on ship operations: Swell direction was nearly perpendicular to the course steered by the PT. EVANS *(see heading diagram)*. This often resulted in the cross swell cancelling out or spilling over cutter-induced primary and secondary bow waves forming to starboard. Oil that was carried on the crests of these bow waves was then observed moving back toward the cutter in response to swell action. As a result, surface oil coverage in the four to six foot wide zone of turbulence created between the hull of the PT. EVANS and the frontside of the bow waves was greater than observed on previous transects run on December 8 into swell and across swell at 45° . This swell influenced response was not repeated on the portside, where the cutter hull effectively shielded developing primary and divergent bow waves from the swell. Disturbance of surface oil to port was minimal, since the bow waves were smaller than those generated to starboard and generally nonbreaking. Whether this near ideal situation of having large concentrations of oil close to both sides of the hull would be repeatable in higher sea state conditions is questionable. It is highly probable that a better developed cross swell would increase roll as a vessel proceeded down the swell trough with a concomitant increase in "splash out" of oil to both sides.

Wind had no noticeable effect on the PT. EVANS on this run.

F. OIL SLICK FATE AND BEHAVIOR IN RESPONSE TO VESSEL OPERATIONS

1. General Observations

a. Film Thickness - It was generally observed that there was a strong correlation between oil slick displacement and oil film thickness given the same vessel, oceanographic and meteorological parameters. Basically, the thicker the surface oil film the greater the tendency for a slick to resist physical displacement (i.e., turning under or pushing out) and remain on the surface. This held true even when the cutters were producing breaking bow and stern waves.

Transects 2 and 3 completed on February 21, 1978 clearly display this correlation. The transects were run at average speeds of 4.4 knots and 5.5 knots, respectively, through slicks that varied from very thin patches of silvery sheen oil to medium thick windrows of chocolate mousse. On both runs, the thinner slicks were often churned up and entrained in the water column or pushed out by wave action. The churned under oil normally remained submerged for several seconds before resurfacing toward the stern. Conversely, the thicker oil normally rode over the backside of the breaking waves or, if submerged, resurfaced as soon as it cleared the whitewater. Furthermore, it was noted that the thicker surface oil concentrations greatly retarded bow wave formation during the slower run (Transect 2) and that bow wave height was considerably reduced, and breaking action very irregular, during Transect 3 run at more than five knots. In contrast, bow waves formed irregularly through thin slicks at 4.4 knots and consistently at 5.5 knots.

The correlation between oil film thickness and slick displacement patterns was not as pronounced in the area affected by stern wave/rotational wake action. Thin to medium thick oil was consistently churned under or pushed out by breaking waves and pulled under the hull by propeller induced suction. Only the very thick emulsified oils encountered on February 21 remained semi-intact and visible in the wake area following a cutter pass.

These general assumptions concerning oil thickness versus surface displacement proved valid through ship speeds of six knots and Sea State 3 conditions during the three test days.

While oil film thickness is an important consideration in terms of placement of sorbent chip spreading equipment to minimize the effect of vessel-induced bow and stern waves on surface oil, this should have little impact on recovery. Surface sampling conducted in the rotational wake of the cutters on each test day showed that recoverable (surface) oil concentrations in that turbulent area were normally within a few mm of the surface concentrations recorded before the cutter transited (Table 3). Thus, while thinner surface

oil may be considerably displaced by bow wave action as a cutter passes, it appears that the positive buoyancy of petroleum will minimize time of entrainment in the water column regardless of oil thickness.

b. Age of Oil - Age of oil is important in terms of fate and behavior and potential for recovery. Based on observations made during this program, earlier sea support efforts in conjunction with natural seep surveys and airborne oil surveillance system tests (Estes and Kraus, 1976; Kraus and Estes, 1976; Kraus et al, 1977), and a search of the literature, the following general statements can be made concerning the surface appearance of crude oil as a function of time:

- Initial contact with the ocean surface, whether from natural seepage or an oil spill, normally results in rapid spreading of a thin silvery sheen to rainbow iridescent layer of oil. According to Sivadier and Mikolaj (1973), the ultimate evaporative weight loss of oil is on the order of 20 to 22 percent. Furthermore, approximately 90 percent of the ultimate weight loss was found to occur within two to six hours of initial contact (depending on sea surface roughness). Rapid evaporation is favored by high winds, rough weather conditions, and increased surface area through spreading. These conditions were experienced in the test area on December 15. Rates of spreading are dependent on oil viscosity, density, chemical composition, and the pour point (Waldman, Johnson, and Smith, 1973). Additional oil is dissolved in water during the first several hours following contact and becomes nonrecoverable.

- As spreading slows with time, oil on the ocean surface normally becomes thicker. This process is further enhanced if sea and weather conditions are fairly calm. The grey/brown surface oil encountered on December 8, which formed large slicks in the test area, was representative of this stage of aging.

- As oil ages further, the chances of emulsification increase. The most common example of this process is water-in-oil emulsion commonly known as "chocolate mousse". This normally takes from three to five days to form, depending on oceanographic and meteorological conditions. When oil is transformed into this water-in-oil emulsive state, viscosity and specific gravity of the oil is greatly increased. The combined specific gravity is very close to that of water, resulting in the oil maintaining a near submerged state. Much of the oil found in the test area on February 21 was emulsified "chocolate mousse" and had been on the surface collecting dust and kelp debris for the previous five to seven days.

In terms of recovery of oil with sorbent materials, the silvery sheen through grey/brown oils present few problems as they are relatively viscous and easily adhere to the sorbent. Also, their relative thickness is such that percentage oil recovered versus sorbent surface area should be high. Drawbacks are that these thin to medium thick oils often are spreading rapidly, which represents a greater surface area to be covered during clean up. Also, as noted in Section F.1.a., Oil Film Thickness, the thinner the surface oil, the greater the probability of vessel-induced waves submerging or pushing it out away from the spreading equipment. Conversely, while the very thick "chocolate mousse" type oils may be fairly resistent to wave action, their chemical properties are such that adherence to sorbent materials is reduced, requiring longer contact time or multiple applications to recover this aged oil.

c. Vessel Speed - This was the most significant vessel-related factor affecting oil fate and behavior during the sea tests conducted in the Santa Barbara Channel. Noticeable differences in the formation of primary and secondary (divergent) bow waves and stern waves, responsible for churning surface oil under or pushing it out, were observed as the cutters operated at different speeds.

- For example, during the two low speed runs (completed at an average transect speed of three knots or less), small bow waves generated by the cutters PT. HOBART and PT. JUDITH did not break. The effect of these nonbreaking waves on surface oil was to stretch the slicks slightly. Once the waves passed, the slicks contracted and resumed their original profiles. In all cases, the oil was observed to pass alongside the cutter's hull relatively intact. Entrainment of oil through submergence is considered highly unlikely within this speed envelope, although subsurface sampling would be required to confirm the assumption.

  Stern wave/rotational wake action also was minimal. Most of the oil proceeding along the hull was momentarily piled up at the edge of this turbulent zone, with intact oil actually observed in the wake turbulence area on the low speed run of February 21. During both transects, surface concentrations of oil in the wake areas were almost identical to those measured ahead of the cutters at the same location.

- The occurrence of breaking bow and stern waves was first observed during middle speed runs (three to six knots). As ship speeds reached three knots, induced bow and stern waves began to break irregularly. Minor mixing of oil into the water column was evident, as was occassional pushing out of surface oil to a distance some three to four feet out from the cutter's waterline. This latter phenomena was observed only when divergent

(secondary) bow waves broke. When the secondary waves were not breaking, surface oil proceeded along the hull in a near continuous slick.

Four knots into the swell represented the threshold hull speed and general heading at which breaking bow and stern waves normally began forming. On both runs where this speed and direction were maintained for several minutes, the presence of well-developed, breaking divergent bow waves was noted. Whitewater from the breaking waves was observed on film and during the actual runs to contain globules of tarry oil, and almost certainly resulted in some entrapment below the surface. Surface oil from the displaced slicks also rode down the frontside of breaking waves and was pushed up on undisturbed oil approximately five to seven feet from the hull.

This disturbance pattern extended eight to ten feet from the cutter as speed was increased from 4.0 knots to 4.4 knots (Transect 2, February 21). Significant disruption of oil slicks on that specific transect was rather infrequent due to heavy concentrations of aged surface oil. Instead, an estimated 85-90 percent of this oil surfed down the backside of the bow waves and remained on the surface alongside the cutter. Whether this pattern would be repeated in thinner oil conditions and heavier seas at speeds of under five knots is unknown. Results from runs made at five knots or more through thinner oil showed greater disruption of slicks.

In comparison to the low speed (i.e., under three knot runs), stern wave height and wake turbulence action increased significantly at speeds of three to five knots. Oil was typically pushed out three to five feet from the stern or pulled under the hull where it entered the rotational wake. Small patches of extremely thick oil were occasionally observed floating on the surface in the wake turbulence zone. Surface sampling again established the fact that recoverable oil in the stern wake, while not readily visible except in isolated patches, was present in quantities approximately equal to those sampled before the cutter passes.

- Three runs of six knots or more completed on December 8 resulted in the formation of well developed primary and secondary divergent bow waves and breaking stern waves. The effects of these ship-induced waves on oil slicks were variable, depending on the direction steered and slick thickness characteristics, although several general observations can be made. For example, intact slicks were consistently cut by breaking divergent bow waves which rolled considerable amounts of oil underwater or ten to twelve feet out from the cutter on the frontside of the waves. While no surface oil was observed in the whitewater along the wave crests, come oil did manage to surf down the

backside of the eight to ten inch high cresting bow waves just prior to their breaking. Submerged oil could be seen resurfacing approximately ten to fifteen feet down hull from the wave crests and joining oil that had surfed down the waves. Additional patches of intact, undisturbed oil swept in behind the dissipating bow waves. The slicks ran approximately parallel to and five feet off the cutter's hull. These were non-contiguous and periodically broken by a thin zone of turbulent water that also paralleled the cutter. Occasionally, oil ran closer to the hull (e.g. within one to three feet), particularly to the lee side when the cutter was running at an angle across swell or in the trough of the swell. These conditions are documented on still and motion picture film.

When the oil reached the stern, it appeared to be pushed out three to five feet from the wake by the stern waves, with the remaining oil either sliding down the backside of the stern wave into the wake or sucked under the hull. The stern wakes were an estimated 20-25 feet wide. Once again, oil samples taken in the wake showed little variability in oil thickness, compared to samples from the same area just before the cutter passed. This occurred despite the apparent oil free reflectance characteristics of the wake area on film.

In terms of oil recovery probability, the six knot runs were the least promising due to the well developed bow and stern waves that consistently disrupted surface slicks and turned oil under.

d. <u>Vessel Direction (In Relation to Swell/Wind Direction)</u> - Because of the relatively calm sea conditions experienced throughout the test program, vessel direction, in relation to swell and wind direction, seemed to have only a minor impact on oil slicks. Howeven, subtle differences in oil displacement patterns in relation to vessel headings were noted during the three test days that could be of considerable importance in planning oil recovery operations under higher sea state conditions. These observed differences are documented below. Emphasis is placed on vessel/swell interactions, since wind seemed to have very little impact on oil slick displacement.

Basically, the nine transects can be classified into four broad categories based on vessel heading/swell direction interrelationships. These categories are:

- into swell (vessel direction within $\pm$ 15° of swell)
- cross swell (vessel direction with $\pm$ 30° to 45° of swell)
- along the trough (vessel direction approximately 90° to swell)
- with swell (vessel direction within $\pm$ 15° of swell)

Three transects were run into swell and across swell, two along the trough, and one with the swell.

- Into the swell - Transects steered approximately into the swell (± 15°) were completed on each of the test days. Vessel speeds were 2.3 knots (December 15, Transect 1), 3.6 knots (February 21, Transect 1), and 6.2 knots (December 8, Transect 1). In all cases, vessel-induced oil displacement patterns were very regular, with approximately equal quantities of surface oil noted on both sides of the cutter. This was true even on December 15 with strong 15 knot winds from approximately 45° off the port bow of the cutter and 30° from swell direction were recorded. At lower speeds (four knots and under), with nonbreaking bow waves, oil passed the cutters relatively undisturbed and within a foot of the hull. On the one six knot, high speed run (December 8, Transect 1), the breaking bow wave initially pushed oil ahead of the cutter or out. However, displaced oil was observed immediately resurfacing or slipping back into the zone of turbulence and reforming into semi-contiguous slicks approximately three to five feet off the cutter.

- Cross Swell - The three transects run across swell were at 45° (December 8, Transect 2), 30° (December 15, Transect 3), and 35° (February 21, Transect 3). Vessel speeds were 6.6 knots, 5.0 knots, and 5.5 knots, respectively. Considerable variation in oil displacement patterns was evident when viewing imagery for each of the runs. During the December 8 transect, with low 1-1/2-3 foot swells, frequent turning under and pushing out of oil was observed on the starboard side of the cutter PT. EVANS in response to breaking bow waves. Conversely, the bow waves to port broke irregularly and oil flowed along the cutter's hull. This difference in bow wave formation and breaking action was interpreted to be a consequence of the cutter running across swell. While the oncoming swell pushed over bow waves from starboard, it had little effect on waves to port due to the cutter's screening action.

  The December 15 transect was run across a three to four foot swell coming from port to starboard. This resulted in severe splash out of oil and water to port, due to the vessel's hull lifting out and reentering the water, with lesser displacement to starboard. Again, the cutter hull seemed to slightly shield surface oil concentrations away from the swell direction, although the vessel speed and moderate sea swell combined to force oil out considerable distances from port (eight to twelve feet) and starboard (six to eight feet).

  The February 21 run, across a one to two foot swell, resulted in no measureable differences in bow wave action or oil displacement to either side of the vessel. This was attributed to the calm sea conditions and low swell.

- <u>In the Trough</u> - The transects completed along the trough of the swell were run on December 8 (Transect 3) and February 21 (Transect 2). The December 8 transect was run at six knots; the February 21 transect at 4.4 knots. Both transects were with the swell from starboard to port. Little difference in bow wave formation breaking action was noted on February 21. As vessel speed passed four knots, bow waves broke fairly regularly on either side of the cutter. Oil was churned under or pushed out from five to seven feet off the PT. JUDITH, but reformed within one or two feet of the cutter's hull upon reaching amidships. The low one to two foot swell seemed to have virtually no impact on frequency of occurrence or wave height.

  The December 8 run produced more interesting results for oil recovery planning. Primary and secondary bow waves were consistent this run, especially to starboard where the divergent waves rose rapidly before being pushed over and cancelled by the oncoming swell. During initial wave formation, surface oil was pushed away from the hull or mixed in the whitewater caused by the breaking wave crests. Surprisingly, large patches of oil were observed surfing down the backside of breaking waves or sloshing back toward the cutter from behind cancelled bow waves. As a result, oil covered much of the sea surface adjacent to the cutter despite substantial swell/bow wave interaction. Ship generated waves to the sheltered portside were smaller and more regular.

- <u>With the Swell</u> - The one transect run with swell was completed on December 15 (Transect 2). Swell height was moderate (three to four feet) and vessel speed was 3.9 knots. The run was steered 15° off swell (coming from starboard to port). Oil displacement to either side was minimal. There was little evidence of breaking bow waves. In most cases, surface oil would stretch as nonbreaking bow waves moved through the slick, then contract after the waves passed. Oil was seen, in many instances, passing directly along the hull from bow to stern. There was no lifting of the bow and splash out of oil or water, despite the swell height and speed.

2. <u>Summary Conclusions</u>

Based on analysis of nine vessel runs completed December 1977 and February 1978, it is our conclusion that vessel speed and direction in relation to swell height/direction and, to a lesser extent, wind speed/direction are the most significant factors to be considered in planning for maximum oil sorbent dispersal/ recovery success. The conclusions presented below consider

these primary factors as well as summarizing the general effect of vessel operations on oil film thickness characteristics. It should be noted that these conclusions are based on data specific for U.S. Coast Guard 82-foot patrol cutters and that the surface oil sampling program, while providing useful qualitative data, is not considered statistically significant due to the limited number of samples taken.

a. Vessel Speed - Vessel speed was the most significant factor affecting changes in surface oil patterns attributed to vessel operations. During the course of the test program, it was noted that oil displacement increased in most instances with increased ship speed. Specifically, noticeable differences in the formation of primary and secondary bow waves and primary stern waves, which turned oil under or pushed it out, were observed at different operating speeds. For example:

- at lower speed (i.e., three knots or less) oil slicks would generally run undisturbed alongside a cutter's hull and provide excellent targets for oil chip dispersal and recovery. Oil displacement patterns were generally independent of swell and wind height/direction at these lower speeds.

- As ship speeds increased through three knots, slicks were frequently disrupted by breaking bow and stern waves which churned oil under near the bow and forced remaining surface oil approximately three to seven feet away from the hull. This action also created a zone of turbulence alongside the hull where oil alternately resurfaced then submerged depending on direction into the swell.

- At speeds of six knots or more, and occasionally at lower speeds, oil was pushed away from the cutters by waves that formed off the stern. Primary and divergent bow waves formed consistently at speeds in excess of five knots and pushed oil under (ahead of the bow waves) or out from the cutter hull (seven to twelve feet).

To maximize oil recovery potential, it is recommended that vessel speeds of three knots or less be used, when possible, to reduce oil displacement by ship generated waves.

b. Vessel Direction - Although this parameter had a minimal impact on surface oil displacement patterns exhibited during the test program, subtle differences in vessel direction in relation to swell and wind direction were observed. These could be of considerable importance in planning for oil recovery under higher sea state conditions (i.e., Sea State 4 and above). For example:

- steering into the swell (i.e., $\pm$ 15°) consistently resulted in vessel generated bow waves (breaking or nonbreaking) with similar oil displacement patterns observed on both sides. This would permit dispersal of oil sorbent material to either side of the cutter with equal results.

- Heading across the swell (i.e., 30° - 60°) provided a sheltering effect to the lee side of the cutter and often resulted in surface oil concentrations remaining relatively intact. This effect was especially apparent when bow waves were nonbreaking on the lee side and oil could be observed sliding down the hull. Conversely, oil toward the oncoming swell was considerably mixed or pushed away from the cutter when breaking bow waves were generated. The occurrence of breaking bow waves was more frequent to the swell side. Oil recovery operations under these swell conditions would be maximized by dispersing the oil sorbent chips to the lee side.

- Heading along the trough of the swell (i.e., ≈90°) resulted in little disruption of surface oil to the lee side of the cutter (away from swell) and considerable concentration of oil in the direction of swell. The latter occurrence was due to the swell cancelling ship generated bow waves and forcing oil back in toward the hull. In low sea state conditions, where the swell would not cause excessive ship pitch, roll, and yaw, the trough facing the oncoming swell would appear to be a prime area for dispersal of sorbent materials due to the regular concentration of surface oil from amidships aft. The sheltered lee side would provide a secondary placement area for chip dispersal.

- Heading with the swell (i.e., $\pm$ 15°) appears to be an optimum direction to steer, especially in heavy seas. Porpoising of the cutter was kept to a minimum during a run completed with three to four foot swell and 15 knot winds. No "splash out" occurred at four knots. Oil was observed sliding along the cutter within a foot or two of the hull. Dispersal of sorbent chips could be accomplished equally off both sides of a vessel.

c. Oil Film Thickness - Several significant conclusions regarding the effects of transiting vessels on oil film thickness were reached during the course of the data analysis program. These may be summarized as follows:

- when bow waves did not break (i.e., at speeds of three knots or less), oil remained relatively intact on the ocean surface. While the nonbreaking bow waves would stretch a slick, the surface oil would pull together again and

(presumably) resume its original thickness after the wave passed.

- Oil carried on the crest of breaking bow waves would momentarily pile up on undisturbed oil at the breaking wave/calm water interface. These buildup zones were approximately two to six inches wide and remain intact for only a second or two. Characteristically, the oil would then be swept back into the zone of turbulence behind the dissipating breaking wave and parallel to the boat hull. Sampling on the wave crests and in the following troughs yielded little quantitative data for determining changes in thickness within the narrow buildup zones. Regardless, these zones seem to be of little interest in terms of oil recovery due to their ephemeral nature.

- Oil churned under by bow waves and trapped subsurface in the water column apparently remains in suspension for only a short period of time. During each transect, oil was consistently observed resurfacing in the area behind breaking bow waves within a few seconds of entrainment. Unfortunately, no useable subsurface sampling data were available to accurately estimate the total percentate of submerged oil that resurfaced along the hull.

- Although the wake zone may appear oil free to the naked eye and on photographic imagery, it nevertheless contains significant amounts of recoverable oil. For a given location, concentrations of recoverable (surface) oil in the ship wake zone appear to vary insignificantly compared to quantities of surface oil present before a vessel passes.

- Thicker oil concentrations are affected less by vessels than are thinner oil slicks. The heavy, emulsified oil encountered on February 21 was observed to enter the wake area relatively intact and form discrete surface concentrations. Thinner oil was broken up and entered the wake in noncontiguous surface concentrations.

G. RECOMMENDATIONS

The following recommendations for vessel operating speeds and headings during oil recovery operations and the placement of oil dispersal and retrieval equipment onboard are based on nine vessel runs completed through oil slicks using U.S.C.G. 82-foot patrol cutters. It should be noted that the test vessels were not equipped with variable pitch propellors, which hindered manuevering and operability at speeds under six knots, and that the relatively shallow draft of these vessels greatly retarded the formation of well developed primary and secondary bow waves. This latter point is particulary noteworthy, since displacement of surface oil by larger vessels-of-opportunity might be more pronounced, especially if deep draft, wide bottomed vessels are employed. Any tendency by larger vessels to create breaking bow waves would be greatly reduced, however, if the ships were equipped with variable pitch propellers which permit low speed operations and non-generation of bow waves. While the findings of this report are specific to 82-foot patrol cutters, many of the conclusions and recommendations should be directly transferable to larger vessels.

1. Vessel Speed - To maximize oil recovery potential, it is recommended that vessel speeds be kept to a minimum to prevent the formation of regularly breaking bow and stern waves. These breaking waves tend to turn oil under or push it out and away from a recovery vessel, rather than allowing the oil to run relatively undisturbed alongside the hull. In the case of the shallow draft 82-foot cutters, speeds up to three knots are possible before bow waves begin to break. In deeper draft vessels, maximum speeds probably should not exceed two knots.

2. Vessel Direction - In relatively low sea state conditions (Sea State 3 or less), a number of vessel directions in relation to swell and wind directions can be steered without greatly reducing oil recovery potential. During the tests, the cutters steered into the swell (+ 15°), with the swell (+ 15°), across the swell (30°-45°), and along the trough (perpendicular to the swell). Steering into the swell and with the swell resulted in similar oil displacement patterns to both sides of the cutter. These appear to be the optimum headings under most conditions, since oil sorbent material could be dispersed to either side of the vessel with equal results.

   At higher sea states (i.e., Sea State 4 and above), heading with the swell appears to be the optimal direction. Porpoising of a vessel would be kept to a minimum and very little "splash out" due to the hull being lifted out of the water would occur. Again, oil could be recovered from either side of the vessel. Further research is needed to document vessel-oil interactions under adverse weather conditions, since it is likely that many open ocean recovery operations would be conducted in less than favorable conditions.

3. <u>Oil Film Thickness</u> - To maximize oil recovery potential, regardless of slick thickness, it is recommended that recovery operations be conducted in such a manner that bow wave formation is minimized. Naturally, thicker oil slicks will require greater concentrations of sorbent materials on the surface to recover available oil than thinner, more viscous slicks.

4. <u>Location of Sorbent Dispersal and Recovery Equipment</u>
   a. <u>Single vessel operations</u> - The optimum locations for oil chip dispersion and recovery devices onboard vessels is extremely dependent on a combination of factors, including vessel size, available deck space, and the actual size of the dispersion/recovery equipment. Since firm specifications for the MSORS were not provided to GRSU by CEL, these recommendations must be very general in nature. Further, for single vessel operations, it is assumed that maximum oil recovery efficiency with least effort is the primary goal. Therefore, it is our recommendation that oil chip dispersal devices be mounted as far forward as possible on any vessel of opportunity and (ideally) on both sides of the vessel. Vessel speeds should be kept to a minimum to prevent the regular formation of divergent bow and stern waves and headings should be into or with the swell whenever possible. Oil recovery equipment should be mounted on either side of the vessel, as far aft as possible, or, towed behind. Towing a recovery device would relieve deck space congestion and reduce the number of units needed, while still insuring a high rate of recovery. In instances where higher operating speeds with concomitant breaking waves might be desireable, a recovery device towed in a ship's wake would be more efficient than stern mounted devices. The former location would permit maximum time for submerged oil to resurface and be recovered.

   b. <u>Two vessel operations</u> - This scenario envisions one vessel laying down sorbent chips and another vessel providing recovery. Again, these recommendations are general due to the lack of engineering data on the MSORS. If two or more vessels are used, it is recommended that oil sorbent dispersal equipment be mounted well forward on the lead vessel, and that the recovery device be towed behind the second vessel, if possible. Ship speeds should be synchronized to minimize disruption of surface oil prior to chip spreading and during recovery.

   A final comment concerning the suitablility of USCG 82-foot patrol cutters for oil recovery is warranted. In our opinion, the vessels are not efficient dispersal/recovery platforms due to their small size, shallow draft, inability to operate at low speeds for continuous periods, and general

instability during moderate and high sea state conditions. Large oil work boats in the 150-200 foot class or ocean-going tugs appear to be more suitable vessels for this type of operation.

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APPENDIX A

SAMPLING PROCEDURES IMPLEMENTED DURING THE DECEMBER 2, 8, AND 15, 1977 AND FEBRUARY 21, 1978 SEA CRUISES

I. December 2, 1977 Sea Cruise

The basic purpose of the December 2 sampling effort was to train GRSU personnel on the use of the "cookie-cutter" surface sampling devices and to evaluate possible surface and subsurface sampling schemes. No subsurface sampling was attempted due to the nonavailability of the pump/hose sampling device which was being assembled at UCSB. The following surface sampling program was used on December 2 when the Coast Guard Cutter PT. EVANS ran four transects through oil seeps off Coal Oil Point (see Figure A-1):

SAMPLING PLAN (From UCSB Whaler)

Whaler Location/Station	Relative Time Sequence	No. and Type Samples
1. In path of cutter	≈2-3 minutes before pass	two(2)cookie-cutter
2. Off path of cutter		
On crest of bow wave	At time of pass	one(1) cookie-cutter
In trough of bow wave		one(1) cookie-cutter
3. In wake of cutter	≈1-2 minutes after pass	two(2) cookie-cutter
4. Off path of cutter (same location as 2)	≈3-4 minutes after pass	two(2) cookie-cutter

TOTAL: 32 samples (8 per run; all surface)

No major operational difficulties were encountered during sampling and the following conclusions were drawn based on the day's activities:

- The four sampling locations selected should provide a reliable data base for determining relative changes in surface oil thickness due to vessel operations. One additional subsurface sampling location should be added just off the path of the cutter, to account for possible oil entrainment (subsurface sampling was already planned for Stations 1, 3, and 4).

- Sampling operations could be conducted at each station within the time allotted. However, it would not be possible to further reduce the sampling interval between stations due to the time required to: (1) change the sorbent pads in the "cookie-cutters," and (2) maneuver the sampling boat into position.

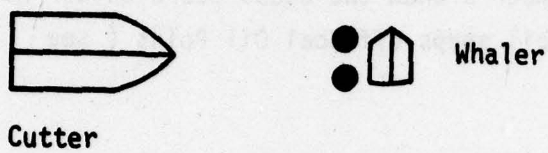
- Three to four samples were desirable at each surface and subsurface location, since oil thickness values for each station would be

FIGURE A-1

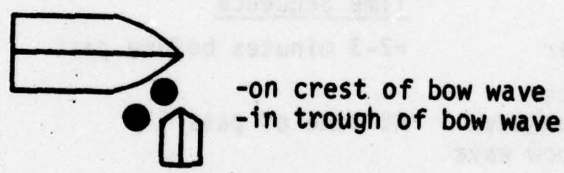
SAMPLING LOCATIONS FOR DECEMBER 2, 1977 SEA CRUISE

● Surface Sample ("cookie cutter")

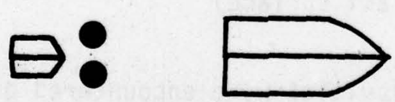
STATION #1 (≈2-3 minutes before pass)



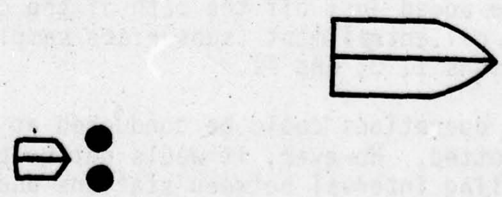
STATION #2 (at time of pass)



STATION #3 (≈1-2 minutes after pass)



STATION #4 (≈3-4 minutes after pass)



TOTAL SAMPLES (4 transects): 32 surface samples ("cookie cutter")

based on averaging the individual samples. This was not possible at Station #2, however, due to the limited availability of "cookie-cutter" devices and the need to sample on the leading bow wave crest and following trough.

II. December 8, 1977 Sea Cruise

GRSU investigators obtained surface samples on December 8 using the "cookie-cutters" and subsurface samples using the pump/hose combination. Subsurface samples were taken at one, three, five, and ten foot depths. A total of three transects were completed by the Coast Guard Cutter PT. EVANS. The sampling plan employed on December 8 is shown below (see Figure A-2):

SAMPLING PLAN (From UCSB Whaler)

Whaler Location/Station	Relative Time Sequence	No. and Type Samples
1. In path of cutter	≈2-3 minutes before pass	three(3) cookie-cutter four(4) subsurface
2. Off path of cutter	≈1 minute before pass	four(4) subsurface
3. Off path of cutter On crest of bow wave In following trough	At time of pass	one(1) cookie-cutter one(1) cookie-cutter
DROP TWO(2) STARCH BOTTLES TO MARK LOCATION		
4. In wake of cutter	≈2 minutes after pass	three(3) cookie-cutter four(4) subsurface
5. Off path of cutter (Same as 2)	≈3-4 minutes after pass	four(4) subsurface

TOTAL: 81 samples (27 per run; 11 surface and 16 subsurface)

III. December 15, 1977 Sea Cruise

The same sampling plan used on December 8, 1977 was implemented on December 15. The Coast Guard Cutter PT. HOBART ran three transects through the test area. A total of 33 surface and 48 subsurface samples were acquired. The strip sampler was tested for the first time although no usable surface oil samples were obtained.

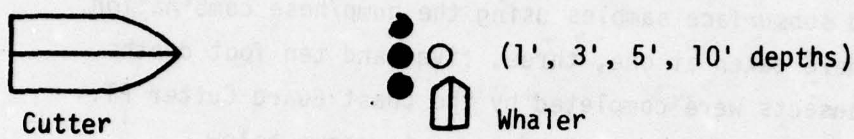
FIGURE A-2

SAMPLING LOCATIONS FOR DECEMBER 8 AND 15, 1977 SEA CRUISES

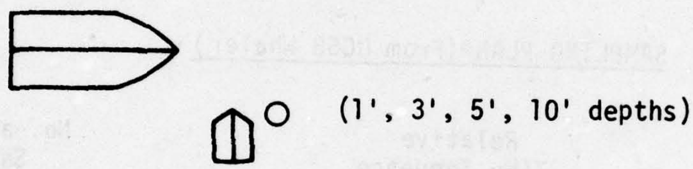
● Surface Sample ("cookie cutter")

○ Subsurface Sample

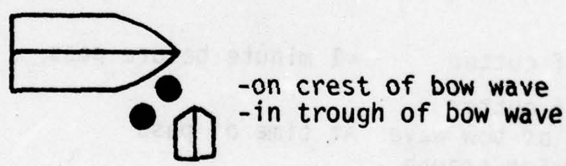
STATION #1 (≈2-3 minutes prior to cutter)



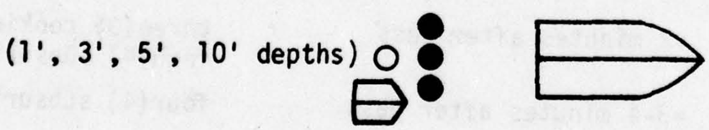
STATION #2 (≈1 minutes prior to cutter)



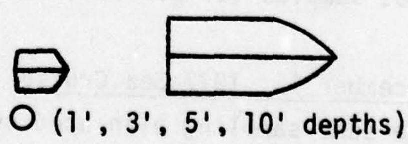
STATION #3 (at time of pass)



STATION #4 (≈2 minutes after pass)



STATION #5 (≈3-4 minutes after pass)



TOTAL SAMPLES (3 transects): 11 surface; 16 subsurface

IV. February 21, 1978 Sea Cruise

The Coast Guard Cutter PT. JUDITH ran three transects through oil on February 21. Surface oil samples were obtained from the Whaler using the "cookie-cutters" and PT. JUDITH using the multiple-station strip sampler. No subsurface sampling was attempted due to the negative laboratory analysis results from the December 8 sea cruise. The following sampling plan was used on this date (see Figure A-3):

SAMPLING PLAN (From UCSB Whaler and USCGC PT. JUDITH)

Vessel Location/Station	Relative Time Sequence	No. and Type Samples
1.* In path of cutter	≈2 minutes before cutter pass	four(4) cookie-cutter
2.x Approaching whaler	Just prior to passing whaler	six(6) per run@
3.* Off path of cutter		
On crest of bow wave	At time of pass	one(1) cookie-cutter
In following trough		one(1) cookie-cutter
4.x In wake of cutter	≈2 minutes after pass	four(4) cookie-cutter
5.* Off path of cutter	NOT SAMPLED DUE TO AVAILABILITY OF MULTIPLE LOCATION STRIP SAMPLES	

TOTAL: 42 Samples [16 per run (Runs 1 and 2); 10 per run (Run 3)]

---

* UCSB Whaler

x USCGC PT. JUDITH

@ Runs 1 and 2 only

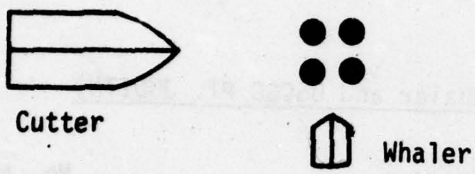
FIGURE A-3

SAMPLING LOCATIONS FOR FEBRUARY 21, 1978 SEA CRUISE

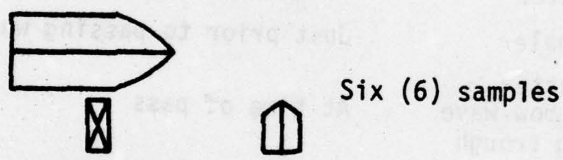
● Surface Sample ("cookie cutter")

⊠ Surface Samples (strip sampler)

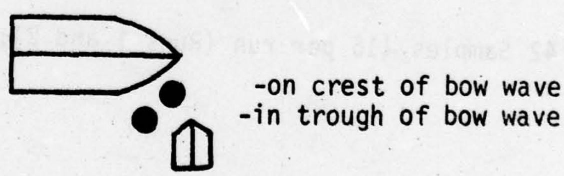
STATION #1 (≈ 2 minutes before cutter)



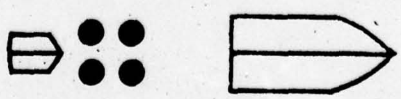
STATION #2 (≈ 100 feet before passing whaler)



STATION #3 (at time of pass)



STATION #4 (≈ 2 minutes after cutter)



TOTAL SAMPLES (3 transects): 42 surface (30 "cookie-cutter"; 12 strip sampler)

APPENDIX B

CALIBRATION PROCEDURES AND RESULTS OF SURFACE OIL FILM THICKNESS MEASUREMENTS

CALIBRATION PROCEDURES

The sorbent material used for surface sampling was 3-M Brand Type 156 oil sorbent. From previous use of this material, it has been determined that a single layer will absorb oil up to approximately two (2) mm in thickness. A contact time of five (5) to ten (10) seconds is adequate to remove all surface oil from the water surface.

The gravimetric method was selected by UCSB chemists for measuring the quantity of oil contained in the sorbent. While time consuming, this procedure was simple and inexpensive to implement and produced accurate results. The method involved adding 500 ml of n hexane, Mallinckrodt grade A. R. as a solvent to a sample jar containing the oil soaked sorbent pad. The solvent was selected on the basis of its miscibility with oil, its immiscibility with water, and its low boiling point. The jar was closed and allowed to stand overnight. The sorbent pad was then squeezed "dry" and the extraction procedure was repeated a second time.

Following this, the two quantities of hexane were combined and treated with anhydrous sodium sulfate to remove entrained water. The solvent was then evaporated using a Buchi, Rotovapor-R down to about 20 ml and transferred to a 50 ml beaker. The round bottom was rinsed twice with 10 ml portions of hexane. The remaining hexane was removed by heating at the lowest setting on a Corning PC-35 hot plate. The weight of residue oil was then recorded to the nearest one hundredth of a gram.

The measured weight of oil in each sample was then converted to a representative oil film thickness value using a method developed by Mikolaj (Estes, Mikolaj, and Thaman, 1972).

Two correction factors were required to convert the measured weight of oil, W_m, to the true weight of oil contained in the sorbent, W. These factors were W_b, the weight of solvent extractable material in a blank sheet of sorbent; and W_r, the residual weight of oil remaining in the sorbent after extraction. Based on five separated measurements, it was determined that $W_b = 0.11$ gm/ft^2 of sorbent; the maximum deviation was $\pm$ 0.04 gm/ft^2.

The W_r correction term was determined by considering a sorbent sheet which contained W gm of crude oil that had been mixed with a volume V_1 of solvent (Because of sorbent porosity, a volume of this solvent, V_{sat}, remained in the sorbent after it was pressed "dry"). Since the amount of oily solution recovered was $V_1 - V_{sat}$, the amount of oil remaining in the sorbent was $W(V_{sat}/V_1)$. A second extraction with a volume of V_2 of solvent then left a residual amount of oil equal to $W(V_{sat}^2/V_1V_2)$. Since $W = W_m + W_r$, and assuming $W_r << W_m$, the correction factors became:

$$W_r = W_m(V_{sat}^2/V_1V_2) \tag{1}$$

Several measurements of the saturation volume showed that V_{sat} = 45 ml solvent/ft^2 of sorbent; the maximum deviation was $\pm$ 10 ml/ft^2.

Once the true weight of absorbed oil, W, had been established, the oil film thickness was computed from the following equation:

$$t = \frac{10W}{dA} = \frac{10\ W_m + (W_r - W_b)A^1}{dA} \tag{2}$$

The terms in this equation (other than those already described) are:

t: average oil film thickness, mm.

A^1: area of sorbent sheet, (2.25 ft^2).

A: area of oil slick sampled.

d: oil density (0.9167 gm/cm^2).

The density of the crude oil used in the computations was d = 0.9167 gm/cm^2. Based on the relative accuracy with which each of the variables in equation (2) could be measured, the nominal accuracy in oil film thickness was set at $\pm$ 0.005 mm.

RESULTS

Laboratory analysis of surface oil samples collected on December 8 and 15, 1977 and February 21, 1978 was completed by chemists at UCSB using the gravimetric method (see Section C.2).* On December 8 and 15, 33 oil film samples were collected; on February 21, 42 oil samples were obtained, 30 with the "cookie cutters" and 12 with the strip sampler. The test results for these three sampling days are summarized in Table B-1. Each sample is identified by date, transect number and location in relation to the Coast Guard cutter. Three designations are given for the oil film thickness. The class indicates the general nature of film thickness in the vicinity of the slick that was sampled. These classifications were made visually by GRSU personnel at the time each sample was taken. The thickness designations are:

Symbol	Descriptor	Oil Film Appearance	Nominal Thickness Range(in.)
T	Thin	Silvery Sheen-Iridescent Rainbow	0.0001 and less
M	Medium	Dull Iridescense w/Brown Streaks	0.0001 - 0.001
H	Heavy	Dull Grey/Brown-Chocolate Mousse	0.001 and greater

The millimeter and inches figures in Table B-1 show the actual thickness for each sample as determined by laboratory analysis.

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* Samples for December 2, 1977 were not analyzed due to lack of substantive correlative sea truth data.

TABLE B - 1

RESULTS OF SURFACE OIL FILM SAMPLE MEASUREMENTS

I. "COOKIE-CUTTER" SAMPLES

Date	Transect #	Sample Location*	Film Thickness[x] Visual Appearance	Film Thickness[x] Measured mm.	Film Thickness[x] Measured in.
12/8/77	1	A	M	0.062	0.002
"	"	A	M	0.070	0.003
"	"	A	M	0.075	0.003
"	"	B-1	M	0.070	0.003
"	"	B-2	M	0.068	0.003
"	"	C	T	0.074	0.003
"	"	C	T	0.074	0.003
"	"	C	T	0.081	0.003
"	"	D	M	0.044	0.002
"	"	D	M	0.047	0.002
"	"	D	M	0.051	0.002
"	2	A	M	0.066	0.003
"	"	A	M	0.063	0.003
"	"	A	M	0.068	0.003
"	"	B-1	M	0.068	0.003
"	"	B-2	M	0.062	0.003
"	"	C	T	0.064	0.003
"	"	C	T	0.066	0.003
"	"	C	T	0.075	0.003
"	"	D	M	0.066	0.003
"	"	D	M	0.068	0.003
"	"	D	M	0.074	0.003
"	3	A	M	0.074	0.003
"	"	A	M	0.077	0.003
"	"	A	M	0.054	0.002
"	"	B-1	M	0.063	0.003
"	"	B-2	M	0.063	0.003
"	"	C	T	0.062	0.003
"	"	C	T	0.059	0.002
"	"	C	T	0.063	0.003
"	"	D	M	0.064	0.003
"	"	D	M	0.061	0.002
"	"	D	M	0.067	0.003

Date	Transect #	Sample Location*	Film Thickness[x] Visual Appearance	Measured mm.	in.

I. "COOKIE-CUTTER" SAMPLES (CONT.)					
12/15/77	1	A	M	0.050	0.002
"	"	A	M	0.077	0.003
"	"	A	M	0.125	0.005
"	"	B-1	M	0.208	0.008
"	"	B-2	M	0.262	0.010
"	"	C	T	0.084	0.003
"	"	C	T	0.161	0.006
"	"	C	T	0.073	0.003
"	"	D	M	0.052	0.002
"	"	D	M	0.074	0.003
"	"	D	M	0.062	0.002
"	2	A	M	0.060	0.002
"	"	A	M	0.054	0.002
"	"	A	M	0.057	0.002
"	"	B-1	M	0.026	0.001
"	"	B-2	M	0.058	0.002
"	"	C	T	0.052	0.002
"	"	C	T	0.050	0.002
"	"	C	T	0.028	0.001
"	"	D	M	0.070	0.003
"	"	D	M	0.054	0.002
"	"	D	M	0.057	0.002
"	3	A	M	0.066	0.003
"	"	A	M	0.045	0.002
"	"	A	M	0.044	0.002
"	"	B-1	M	0.056	0.002
"	"	B-2	M	0.044	0.002
"	"	C	T	0.052	0.002
"	"	C	T	0.051	0.002
"	"	C	T	0.050	0.002
"	"	D	M	0.033	0.001
"	"	D	M	0.038	0.002
"	"	D	M	0.044	0.002
2/21/78	1	A	M	0.113	0.005
"	"	A	M	0.115	0.005
"	"	A	M	0.106	0.004
"	"	A	M	0.115	0.005
"	"	B-1	M	0.118	0.005
"	"	B-2	M	0.121	0.005
"	"	C	T	0.104	0.004
"	"	C	T	0.108	0.004
"	"	C	T	0.096	0.004
"	"	C	T	0.045	0.002

Date	Transect #	Sample Location*	Film Thickness[x] Visual Appearance	Measured mm.	in.
		I. "COOKIE-CUTTER" SAMPLES (CONT.)			
2/21/78	2	A	M	0.068	0.003
"	"	A	M	0.068	0.003
"	"	A	M	0.074	0.003
"	"	A	M	0.072	0.003
"	"	B-1	M	0.068	0.003
"	"	B-2	M	0.068	0.003
"	"	C	T	0.086	0.004
"	"	C	T	0.090	0.004
"	"	C	T	0.072	0.003
"	"	C	T	0.079	0.003
"	3	A	H	0.175	0.007
"	"	A	H	0.117	0.005
"	"	A	H	0.189	0.008
"	"	A	H	0.130	0.005
"	"	B-1	H	0.115	0.005
"	"	B-2	H	0.103	0.004
"	"	C	M/T	0.160	0.006
"	"	C	M/T	0.157	0.006
"	"	C	M/T	0.117	0.005
"	"	C	M/T	0.120	0.005
		II. STRIP SAMPLER SAMPLES			
2/21/78	1	S-1	H	0.199	0.007
"	"	S-2	H	0.137	0.005
"	"	S-3	H	0.125	0.005
"	"	S-4	H	0.200	0.008
"	"	S-5	H	0.138	0.005
"	"	S-6	H	0.121	0.004
"	2	S-1	M	0.156	0.006
"	"	S-2	M	0.109	0.004
"	"	S-3	M	0.120	0.004
"	"	S-4	M	0.096	0.003
"	"	S-5	M	0.078	0.003
"	"	S-6	M	0.074	0.002

* Sample locations are as follows (also see Appendix A):

A - In path of cutter (prior to run)
B-1 - On crest of bow wave from cutter
B-2 - In trough of bow wave from cutter
C - In wake of cutter (≈1-2 minutes later)
D - In area where bow wave sampled (≈3-5 minutes later)

S-1 through S-6 - From side of cutter to eight (8) feet out at 16 inch intervals

x Based on visual appearance as observed by sampling crews:

T - Thin oil; silvery sheen to rainbow iridescence in color ($\approx$.0001 inches or less)

M - Medium oil; dull iridescence with brown streaks ($\approx$.0001 - 0.001 inches)

H - Heavy oil; dull grey/brown - chocolate mousse (0.001 and greater)

APPENDIX C

SEA CRUISE SUMMARIES

I. December 2, 1977 Sea Cruise

PARTICIPANTS:

Surface: USCGC PT. EVANS (82' cutter); UCSB FISH III (21' whaler)
Aerial: Cessna 182 (single-engine, fixed wing)

OIL CONDITIONS IN TEST AREA:

Generally favorable. Surface coverage along transect lines varied from 10-100 percent, with average coverage of 40-50 percent. Several oil slicks ranging in size from 1/4 to 1/2 square miles were available for sea tests. Observed oil color was predominantly silver sheen to iridescent/rainbow with occasional orange jell/chocolate mousse streamers and windrows along slick perimeters. The latter contained (old) emulsified oil mixed with broken kelp fronds, dust and other debris.

OCEANOGRAPHIC DATA:

Swell/Wave - Height (ave.): 2-1/2 - 3' ; Direction (from): 220° and 260°

METEOROLOGICAL DATA:

Wind - Speed (ave.): 4-6 knots, gusting to 10 knots; Direction (from): 220°.
Visibility - Unlimited; Cloud cover - None

TRANSECT INFORMATION (PT. EVANS):

Transect No.	Vessel Heading (to)	Vessel Speed
1	260°	6 knots
2	100°	--"--
3	255°	8 knots
4	100°	--"--

DATA PRODUCTS ACQUIRED:

Aerial Photography (Cessna 182) - 35mm color slides __X__ ; 35mm CIR slides _____ ; Super 8mm movies __X__ .
Surface Photography (USCGC PT. EVANS/UCSB FISH III) - 35mm color slides __X__ ; 35mm CIR slides __X__ ; Super 8mm movie film __X__ .
Oil Sampling (UCSB FISH III) - "Cookie-cutter" (surface) __X__ ; Subsurface _____ .

COMMENTS:

Much of the first cruise was dedicated to coordinating air/sea activities, training personnel in the use of the "cookie-cutter" sampling devices, and determining the optimum film/filter combinations to maximize oil/water contrast and document the wave/wake patterns created by the Coast Guard cutter. The shakedown sea cruise proved most rewarding in terms of working out minor problems in communications between participating vessels and aircraft, designing a surface sampling program for use in future cruises, and selection of the appropriate film/filter combinations to insure high quality photography over water. Two GRSU personnel were checked out on the use of the "cookie-cutter" oil samplers and obtained 32 individual samples during the four transects. Photographers on the Cessna 182 and on the PT. EVANS and FISH III shot more than ten rolls of Kodachrome 35mm slides and eight rolls of Super 8mm film. Brilliant sunshine and clear skies provided less than ideal conditions for photographing oil on water due to high sky reflectance and poor contrast between the oil/water mediums. In addition, aerial photography was further hindered by refusal of the charter pilot to descend below 500 feet over water.

II. December 8, 1977 Sea Cruise

PARTICIPANTS:

Surface: USCGC PT. EVANS (82' cutter); UCSB FISH II (21' whaler).
Aerial: Cessna 182 (single-engine, fixed wing)

OIL CONDITIONS IN THE TEST AREA:

Extremely favorable. Surface coverage along the transect lines was 60-100 percent, with average coverage of 80-90 percent. The entire test area from the offshore kelp beds south to Platform Holly was affected by heavy surface concentrations of oil ranging in color from iridescent/rainbow to dull gray/brown. This was the result of several days of relatively calm weather which allowed seep oil to build up and spread fairly homogeneously across the test site.

OCEANOGRAPHIC DATA:

Swell/Wave - Height (ave.): 1-1/2 - 3'; Direction (from): 245°

METEOROLOGICAL DATA:

Wind - Speed (ave.): 5 knots; Direction (from): 150°
Visibility - 1-1/2 - 3 miles; Cloud Cover - 95 percent

TRANSECT INFORMATION (PT. EVANS):

Transect No.	Vessel Heading (to)	Vessel Speed
1	245°	6 knots
2	200°	--"--
3	150°	--"--

DATA PRODUCTS ACQUIRED:

Aerial Photography (Cessna 182) - 35mm color slides X ; 35mm CIR slides X ; Super 8mm movies X .
Surface Photography (USCGC PT. EVANS) - 35mm color slides X ; 35mm CIR slides X ; Super 8mm movies X .
Oil Sampling (UCSB FISH II) - "Cookie-cutter" (surface) X ; Subsurface X .

COMMENTS:

Best day in the test series for surface oil concentrations in terms of thickness, percent cover, and areal extent. Due to high overcast conditions and near complete cloud cover, sky reflectance was low and oil/water contrast for aerial and surface photography was very distinct. Six rolls of color

and color infrared slide film and six Super 8mm cassettes were shot by GRSU personnel on the Cessna 182. Results were considerably better than those obtained on December 2, due in part to the willingness of the charter pilot to descend below 500 feet. GRSU investigators on the PT. EVANS expended an additional four rolls of color and color infrared slide film and three Super 8mm cassettes. Oil sampling was undertaken on FISH II using both the "cookie-cutters" and subsurface sampler. Thirty-three surface and 48 subsurface samples were taken during the three transects. Attempts to slow the cutter below six knots by reducing engine RPM were not successful.* However, it was suggested by Coast Guard personnel that it might be possible to achieve lower speed on the next test day by shutting down one engine.

* Because the 82-foot class of USCG cutters do not have variable pitch propellors, they attain a minimum operating speed of six knots almost immediately following acceleration and cannot operate below this speed continuously.

III. December 15, 1977 Sea Cruise

PARTICIPANTS:

Surface: USCGC PT. HOBART (82' cutter); UCSB FISH III (21' whaler).
Aerial: USCG Sikorsky HH-52A (turbine-engine helicopter)

OIL CONDITIONS IN THE TEST AREA:

Marginal due to high seas and gusting winds which swept the ocean surface clear of crude oil except in zones immediately above natural seeps. Surface coverage along the transects varied from 25-100 percent. Average coverage was 30-40 percent. As a result, the test vessels were required to continuously change locations to have sufficient concentrations of oil for completing transects. Where oil was present, it varied in color from silvery sheen to dull gray/brown.

OCEANOGRAPHIC DATA:

Swell/Wave - Height (ave.): 3 - 6' ; Direction (from): 240°

METEOROLOGICAL DATA:

Wind - Speed (ave.): 15 knots, gusting to 25-30 knots; Direction (from): 210°.
Visibility - 10 miles (at start of tests) to unlimited (as day progressed).
Cloud Cover - 90 percent (at start of tests) decreasing to 10 percent (as day progressed).

TRANSECT INFORMATION (PT. HOBART):

Transect No.	Vessel Heading (to)	Vessel Speed
1	255°	2.3 knots
2	075°	3.9 knots
3	270°	5.05 knots

DATA PRODUCTS ACQUIRED:

Aerial Photography (Sikorsky HH-52A) - 35mm color slides X ; 35mm CIR slides ____ ; Super 8mm movies ____ ; 16mm movies (Navy) X .
Surface Photography (USCGC PT. HOBART) - 35mm color slides X ; 35mm CIR slides ____ ; Super 8mm movies X ; 16mm movies ____ .
Surface Photography (UCSB FISH III) - 35mm color slides X ; 35mm CIR slides X ; Super 8mm movies X .
Oil Sampling (UCSB FISH III) - "Cookie-cutter" (surface) X ; Subsurface X .

COMMENTS:

Oceanographic and meteorological conditions combined to produce highest seas encountered during the test program. Photographic and sampling conditions were less than ideal, however. The rapidly clearing skies during the morning of December 15, combined with high seas, produced very poor oil/water contrast. Rough seas also made surface and subsurface sampling very difficult. Efforts to slow the cutter below six knots by shutting down one engine and slipping the clutch on the other proved successful. A slow speed run at 2.3 knots was completed on the first transect as was a second run at 4.0 knots.

During the December 15 sea cruise, a helicopter was used as a photographic platform for the first time. This proved extremely useful increasing photograhic efficiency and accuracy and reducing workload on the part of camera personnel who could now follow the transiting cutter at much slower speeds than was possible in the fixed wing aircraft. Five rolls of color slide film and a 16mm movie film were shot from the helicopter by GRSU and USN personnel. Photographers on the cutter used three rolls of color slide film and four Super 8mm cassettes. In addition, a cameraman on FISH III photographed all three cutter passes on a Super 8mm cassette and sampling operations using a 35mm camera and color slide film. Thirty-three surface and 34 subsurface oil samples were taken from FISH III using the "cookie-cutter" and subsurface samplers. In addition, the strip samplers developed by CEL were tested from the PT. HOBART.

IV. February 21, 1978 Sea Cruise

PARTICIPANTS:

Surface: USCGC PT. JUDITH (82' cutter); UCSB FISH II (21' whaler).
Aerial: USCG Sikorsky HH-52A (turbine-engine helicopter).

OIL CONDITIONS:

Fair, with much old oil but very little new oil evident. Surface coverage was spotty, with occasional heavy patches of emulsified oil varying from silver/brown to dark orange in color. Tar balls also were common. Several transects were run along narrow, heavy oil slicks that often extended up to a mile in length but rarely exceeded 25 yards in width.

OCEANOGRAPHIC DATA:

Swell/Wave - Height (ave.): 1 - 2' ; Direction (from): 270°.

METEOROLOGICAL DATA:

Wind - Speed (ave.): 3-5 knots; Direction (from): 200°.
Visibility - 8-10 miles; increasing to 15 miles as day progressed.
Cloud Cover - 10 percent; decreasing to 0 percent.

TRANSECT INFORMATION (PT. JUDITH):

Transect No.	Vessel Heading (to)	Vessel Speed
1	275°	3.6 knots
2	175°	4.4 knots
3	235°	5.5 knots

DATA PRODUCTS ACQUIRED:

Aerial Photography (Sikorsky HH-52A) - 35mm color slides X ; 35mm CIR slides X ; Super 8mm movies ____ ; 16mm movies (Navy) X .
Surface Photography (USCGC PT. JUDITH) - 35mm color slides X ; 35mm CIR slides X ; Super 8mm movies X ; 16mm movies ____ .
Oil Sampling (UCSB FISH II) - "Cookie-cutter" (surface) X ; Subsurface ____ .
Oil Sampling (USCGC PT. JUDITH) - Strip sampler (surface) X .

COMMENTS:

Very calm day. Surface oil cover was spotty with very little fresh oil. Three runs below six knots were completed on this date. A Coast Guard HH-52A helicopter again served as a photographic platform. UCSB provided a 21-foot whaler for surface sampling support. GRSU personnel on the helicopter shot six rolls of color slide, color print, and CIR slide film. A U.S. Navy photo-

grapher shot one reel of 16mm film. GRSU photographers on the PT. JUDITH used three rolls of color slide and four rolls of Super 8mm movie film. Surface sampling was conducted from the whaler, using the "cookie-cutters", and the PT. JUDITH, using the strip sampler. No subsurface samples were taken due to the negative results obtained following analysis of several subsurface samples obtained December 8, 1977.